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SOIL CRUSTS

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PREFACE

Purpose

This publication is based on the research conducted by the scientists associated with the Western Regional Research Project W-66 during the period 1964 to 1970. Significant progress was made toward understanding and improving the management of crusting soils, and the W-66 members felt that a regional publication would be the best way to organize and disseminate the new information. Since the subject is relatively narrow, it was possible to cover most aspects of crusting in a single publication. The first chapter is written for a broad audience, including all those who are faced with practical problems involving soil crusts. Chapters 2 through 5 are more detailed, and provide the technical background required for in-depth understanding of soil crust behavior. In addition to the information presented in this bulletin that has not been previously published, a rather extensive review and discussion of appropriate literature has also been included to provide a balanced approach to the subject.

Acknowledgments

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Dr. D. W. Thorne of Utah State University served as the committee's administrative adviser, and Dr. O. R. Neal served as the adviser from the Cooperative State Experiment Station Service.

Marjorie Miller typed and helped proofread the final drafts of the manuscript and Jeanne Earl drew the figures.

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• CHAPTER 1

Management of Crusting Soils: Some Practical Possibilities

W. Doral Kemper and David E. Miller

A structure develops in the top few millimeters of almost every soil which differs considerably from that of the underlying material. It is characterized by few large pores, a high bulk intensity, and often by platiness, stratification, and orientation of the different sized materials. This layer is often harder than the rest of the soil because it is drier and compounds, such as lime and silica, have been deposited at the surface as water evaporated. Because large pores are absent, this surface layer, or crust, usually has a low saturated hydraulic conductivity and limits infiltration. This is a prime factor causing water runoff and erosion. As the soil surface dries, the crust often becomes hard enough to prevent the emergence of seedlings.

Soils with low organic matter and high silt contents usually have low aggregate stabilities which are commonly associated with soil crusting. High levels of sodium make these problems even more severe. Soils with higher organic matter contents, i.e., 2 or 3% or more, are less susceptible to crusting. This is commonly attributed to long organic molecules acting as glues to hold the particles together in fairly stable aggregates, even when the soil is saturated or disrupted. Organic matter may also reduce swelling pressure forces and wetting rates, and modify surface tension forces—all important factors in agrregate stability. Unfortunately, under row crop conditions, permanently increasing the organic matter in the soil is difficult because continuous cultivation and exposure of new surfaces and accelerated decomposition by microorganisms. A permanent cover crop, such as grass, does tend to increase the organic matter in the soil surface while the sod remains in place, but soon after a return to row cropping the increase is lost. Aggregate stability increases during decomposition of fresh organic matter even though the original organic matter content may not be changed. Other management techniques for controlling soil crusting will be discussed in subsequent chapters.

Controlling Infiltration

Improving water intake

Impact of falling water drops effectively destroys the original structure and causes crusting on the surface soil. Consequently, crusting will be reduced and the infiltration rate of a soil will remain higher if plant cover can be maintained. Pastures, cover crops, small grains, and plant residues such as stubble mulch, will intercept much of the drop energy. As row crops approach maturity, their canopies begin to overlap and give complete cover and shielding from waterdrop impact. However, in the early stage of row crop growth, waterdrop action often seals the exposed soil surface, and the protective cover that develops later is of little help in maintaining high infiltration rates unless the seal is broken up by tillage just before the canopy becomes complete.

The advantage of reducing the time the soil is bare is illustrated by the Australian "wheat and sheep rotation," in which a forage crop, usually clover, follows wheat as quickly as possible, and the land is bare of cover for only a few months. The Australians adapted this rotation primarily for erosion control and the additional livestock feed available. Under their climatic conditions, reducing runoff, by having clover cover, saves almost as much water for the subsequent wheat crop as several extra months of fallow.

A rough surface enhances infiltration, primarily by the surface retention of water in the small holes and depressions. A rough surface covered with large clods also temporarily increases the area available for water infiltration. As the clods erode, the dispersed soil material is washed into the bottoms of the depressions, leaving the sloped eroded surfaces free of fine material and able to adsorb water rapidly.

Conventional tillage equipment may be used to increase the roughness of surfaces, to cultivate on the contour, and to provide pockets in the soil surface (listers or skip listers). Ripping equipment is effective for breaking the soil into large clods and lumps when the top 5 to 15 cm (2 to 6 inches) are hard from being very dry or frozen. Ripping results in very rough surfaces which will usually survive several rainfall events before resealing.

Studies in California have suggested the use of rototillers to "aggresize" soil for seedbed preparation (Hoyle et al., 1972). First the soil is sprinkled with about 1 inch of water. When it has dried sufficiently to operate tractor equipment, it is rototilled and shaped into beds. Although this is working the soil wetter than one would normally recommend, under favorable conditions the rototiller can form many small aggregates which are somewhat stable and resistant to crusting.

Eventually, even rough surfaces are flattened out by raindrop impact and microerosion, and the soil tends to reseal. One means of maintaining water flow into the soil is to deposit coarse organic material in a slot in the soil, commonly called a vertical mulching (e.g., Fairbourn and Gardner, 1972). This material gradually decomposes, but may provide a path for rapid entry of water for several years. However, the slot must remain open and not be covered with soil or it becomes ineffective. Unfortunately, machinery is not yet widely available for the economical installation of vertical mulches.

Surface cover also affects water infiltration during surface irrigation. Trashy furrows or plant residues incorporated into or lying on the surface tend to reduce surface sealing and thus maintain high infiltration rates.

Soil textures often vary widely within a few feet of the surface. Mixing of a high silt surface layer with clays from the B horizon may decrease the crusting tendency of a soil and increase cracking, which can greatly increase water infiltration. Other textural changes, such as bringing up coarser textured materials from the subsoil, may also be beneficial. Some sodium problems in the surface can be improved by bringing up gypsum from deeper soil layers (Rasmussen el al., 1972). Deep plowing (30 inches or more) is now done commercially, but the effect of mixing on infiltration rates, crust formation, and plant growth cannot always be predicted.

Gravel or sand mulches 2-3 cm (about 1 inch) thick will prevent infiltration reduction and reduce runoff, as well as evaporation. Although not practical for general agriculture, results indicate that such treatments may be useful in increasing recharge to groundwater. Weed control may be a problem in such systems. Sieving the gravel out of gravelly and stony soils seems possible for constructing groundwater recharge areas from low value land for a reasonable cost. White gravel saves up to 10% more water than dark materials of the same size (Corey and Kemper, 1968).

Gypsum is sometimes used to increase infiltration on sodium-affected soils. The calcium of the gypsum displaces the sodium from near the surface as the soil becomes wet. The gypsum also maintains a reasonably high free electrolyte content in solution at the soil surface. This helps the soil become flocculated and often increases the infiltration rate. Five-hundred kg/hectare (approximately 500 lbs/acre) may be enough to appreciably increase infiltration rates, even on soils that do not have large amounts of monovalent ions in the surface (Kemper and Noonan, 1970). Good estimates of gypsum requirements can be made from chemical analysis of the soil.

Water rising from a shallow water table and evaporating is a major source of monovalent ions in the soil surface. When the cations are mostly sodium, drainage and gypsum application have long been accepted reclamation measures for bettering soil conditions for plant growth. One of the major benefits is generally a reduction in the crusting of the soil involved.

In developing countries, the availability of manures and relatively high cost of gypsum have encouraged the use of manures to improve the structure of sodic soils. Animal or green manure is commonly incorporated in the soil and followed several days later by basin flood irrigation. Because of the low infiltration rates of sodium-affected soils, water commonly stands on the surface for several days during the leaching irrigation. This treatment has been surprisingly effective in reducing sodium content of calcareous soils. Recent studies (W. T. Franklin, unpublished data, Colo. State Univ., 1973) have shown that addition of organic matter, followed by flooding the surface with water results in from 10 to more than 30% carbon dioxide contents in the soil atmosphere. The carbon dioxide and water form carbonic acid which dissolves calcium from lime in the soil. Calcium ion concentrations in the soil solutions during the flooding period were as high as those in soils in which excess gypsum had been added. These high calcium ion concentrations and the accompanying leaching displace sodium ions from the soil exchange complex and carry it out of the surface soil.

Additional information on the use of gypsum and other soil amendments is given in Chapter 2.

Because soil aggregates disintegrates and slump in a furrow during irrigation, the infiltration rate of row-cropped soils generally decreases throughout the growing season. This decrease must be taken into account in designing irrigation systems. The crusts in the furrows often become thicker and harder and less permeable to water with each wetting and drying cycle (see Chapter 4). Tractor travel in a furrow that is still moist accentuates this effect. The infiltration rate may be temporarily improved by cultivation, but this increases costs, may prune the crop's root system, and encourages furrow erosion. As discussed in Chapter 2, surface mulches and plant residues may eventually prove more practical than tillage for maintaining satisfactory water infiltration rates for irrigated row crops.

An interesting structure often develops under furrow irrigation in high silt soils (Figure 1-1). A thin surface layer of compact soil is underlain by several centimeters with a vesicular structure. This type of structure develops as the number of saturation and drying cycles increase. It is also found under sprinkler irrigation where the soil surface is saturated, and in a wide range of soil textures in greenhouse studies where the soil is frequently wet by surface flooding.

Decreasing water infiltration

Increasing infiltration is generally considered beneficial. However, because much of the water available for cities, industry, and farm reservoirs comes from surface runoff, particularly in arid regions, interest has developed in methods for increasing the runoff from small watersheds. In general, the techniques are the opposite of those for increasing infiltration. Runoff-inducing treatments include reduction of plant cover, smoothing of the surface to prevent surface storage and increase sealing, and treating with sodium chloride to increase the sodium content of the immediate surface and thus encourage aggregate dispersion. When these techniques are used to increase runoff, engineering structures must be constructed to prevent the erosion which would otherwise result from these greater quantities of water moving across the soil surface. Factors at a site favoring its use for runoff include a high sodium content and a high silt and fine sand content, so that the soil crust does not crack as drying takes place.

Chemicals for waterproofing soils are becoming available and may be economically feasible. Examples of such chemicals are benzoxazines, hydroxyethyl, various phenols, and sodium methyl silonolates (De Bono and Letey, 1969). Asphalt and plastic covers can also be used to achieve the same end. Waterproofing soil has considerable arid land agricultural potential, as well as potential for domestic and livestock water supply systems. Encouraging experimental work (Aase and Kemper, 1968; Rauzi et al., 1973) has been caried out on waterproofing strips of farmland, causing runoff onto the adjoining strips which are cultivated. The ratio of waterproofed to cultivated area may be adjusted to the expected precipitation to provide the correct amount of water for crop production without fallow periods or supplemental irrigations. This concept has far-reaching implications for revegetating stripmine spoils and maintaining specific types of vegetation in arid regions.

Figure 1-1. A cross-sectional photograph showing the vesicular structure of a soil crust approximately 2 cm thick.

Improving Seedling Emergence

Irrigation and amendments

One of the most adverse effects of soil crusting is the prevention or reduction of seedling emergence. Since irrigation methods and soil crusting are interrelated, seedling emergence can often be improved by selecting a specific method of irrigation. Saturation and flowing water tend to destroy soil structure and induce crust formation. Furrow or rill irrigation will cause less crusting than a border system, because less surface will be saturated. Running water for a long period in a furrow will generally result in more crust formation than running the water for a short time, again because of the difference in total soil surface area that becomes saturated. With sprinklers, slow delivery rates and small drop sizes reduce crusting because the surface does not become completely saturated and the smaller impact forces of the smaller waterdrops destroy fewer aggregates than faster application rates and larger drops.

In soils with a high sodium content, one method for decreasing the surface crusting and increasing seedling emergence is to apply a narrow band of gypsum directly over the seeded row, using between 100 and 200 kg/hectare (or 200 lbs/acre). This band should be applied immediately after seeding, and preferably from the planting equipment, so that the band coincides exactly with the planted seeds. Phosphoric acid sprayed in a band over the seed row has proven effective in reducing crusting and increasing emergence on lime soils. Other amendments to the seed row, such as asphalt sprays applied at planting, are effective, but they are more costly than gypsum or phosphoric acid. Additional information on amendments is presented in Chapter 2.

If the soil surface can be kept moist until seedlings emerge, the strength of the crust usually remains low. Sprinkler systems with fine spray nozzles and low application rates can be used to maintain a moist surface. Center-pivot sprinkler systems have the potential for keeping soils wet, but because of the high application rates near the edge of the circle they should not be used on soils with low infiltration rates. Use of portable sprinkler systems has proved feasible on the crust-susceptible soils of the Imperial Valley, California. Lettuce and other high-value crops are planted in beds,

and the soil is kept moist for the 7 to 10 days required for emergence. Surface irrigation then may be used and the sprinklers moved to other fields. Besides keeping the crust strength low, sprinkling following planting provides optimum water conditions for germination and displaces salt below the seedling zone. The overall improvement of lettuce stands is sufficient that many Imperial Valley farmers are willing to pay custom sprinkler operators to provide this service. Sprinkler design characteristics may have far-reaching effects on both creating and alleviating soil crust problems. Both water-drop impact on the soil surface and the application rate affect runoff and are discussed in some detail in the following chapter.

The thickest and strongest crusts generally develop at the bottom of depressions or on flat surfaces, where the soil is more likely to become saturated. Consequently, seedling emergence can often be improved by avoiding these areas and planting the seed on the sloping side of a furrow. Materials dislodged by rain or sprinkler drops are eroded to the bottom of the furrow, thus removing the dispersed particles necessary for strong crust formation. This erosion can remove as much as 1 cm (0.4 inch) of soil; consequently this practice should generally be restricted to those seeds which are large enough to be planted several centimeters (at least an inch) below the soil surface.

While investment in special sprinklers for germination may not be justified for low-value field crops, land leveling, bedding of the soil, and placement of seed can often allow furrow irrigation to achieve the desired results. Capillary wetting from furrows can leave the soil with a lower strength crust than sprinkler irrigation. In saline soils, much of the salt present will be moved to the top of the ridge between furrows. To avoid exposure of the seedlings to this high salt concentration, crops are often planted on beds of the type shown in Figure 1-2A. Beds from 50 to 120 cm (20 to 48 inches) wide have been used, depending on the crop grown and the ability of the soil to transmit water (capillary conductivity) from the furrow to the ridge. If the ridge is wetted to the middle, the salt is normally swept past the seed and left at the top of the ridge as the water evaporates.

In some highly permeable or coarse-textured soils, water moves downward faster than it moves horizontally, as indicated in Figure 1-2B. Consequently, large amounts of water must be applied to bring the wetting zones together. Figure 1-2B shows a situation where water was maintained in the furrows for 3 hours. A large portion of the surface does not wet to the midplane and, consequently, does not crust. However, only a limited area near the furrow is sufficiently wetted to promote good germination and seedling emergence. These limited areas on the shoulders of the bed are where seeds should be planted if two rows per bed are desired. Considerable losses of water to deep drainage result under these conditions.

Figure 1-2. Diagrams of planting in beds to avoid crusting and salt damage to seedlings. Parts B and C illustrate successive wetting fronts during and following three hours for which water was kept in furrows.

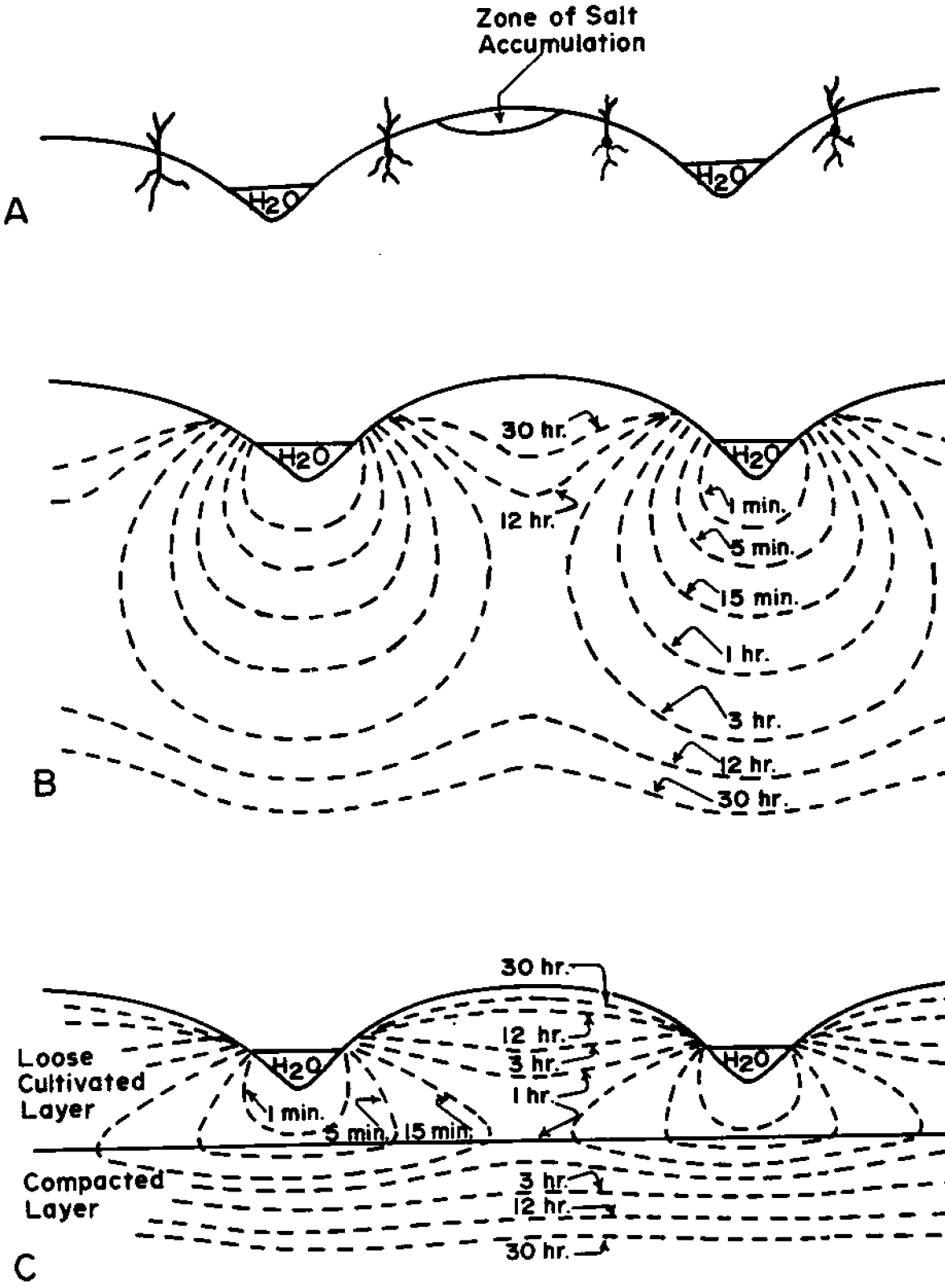
If the surface cultivated layer is underlain by a layer of lower hydraulic conductivity, the water moves from the furrow to the midplane between rows rather quickly (Figure 1-2C). The underlying layer may consist of very coarse or of finer, compacted particles. If the soil has large amounts of pore space in the 0.1- to 0.01-mm-diameter (4 thousandths to 4 ten-thousandths of an inch) size range, water will also move upward to the surface by capillarity through the clods and aggregates. However, poorly structured soils susceptible to crusting usually have relatively small amounts of pores in this size range, and capillary rise through the clods and aggregates is slow. Consequently, water often moves to the surface too slowly to meet the maximum evaporation demand, and a thin, dry layer persists on the surface as indicated in Figure 1-2C. By making the furrows the proper depth in such soils, the low capillary rise characteristics can be used to leave a dry layer 1 or 2 cm (1.4 to 1 inch) thick at the surface, thus avoiding crust formation and reducing evaporation (unpublished studies by John Olsen and W. D. Kemper).

One of the newer methods of irrigation water control is the trickle system now used on some high-value crops. This system involves a slow, intermittent, or constant rate of delivery via plastic tubing and associated orifices. The tubing is laid out on top of the soil and a square meter (10 sq. ft.) or so of surface may be irrigated with each orifice. When water control of this precision can be attained, crusting can usually be eliminated. The possibility of installing permanent underground trickle irrigation systems is also being studied at several locations and potentially offers many benefits, in addition to the control of crusting.

Mechanically destroying crusts

Once a strong crust has formed above germinating seedlings, it is sometimes feasible to break it mechanically. However, such treatment can result in injury to seedlings from crushing or from uprooting as soil moves during the operation.

One type of equipment, sometimes referred to as a cultipacker, that has been used extensively to break up crusts over emerging seedlings is pictured in Figure 1-3. A series of narrow, large outside rings is placed over a smaller supporting tube. This arrangement allows only the weight of individual rings to press on the ground surface, and each ring is free to follow surface contours, thus eliminating skipped or excessively packed areas. The rings fracture or crush the surface


Zone of Salt Accumulation
A
H2O
H2O
B
30 hr.
12 hr.
1 min.
5 min.
15 min.
1 hr.
3 hr.
12 hr.
30 hr.
C
30 hr.
12 hr.
3 hr.
1 hr.
Loose Cultivated Layer
1 min.
5 min.
15 min.
Compacted Layer
3 hr.
12 hr.
30 hr.

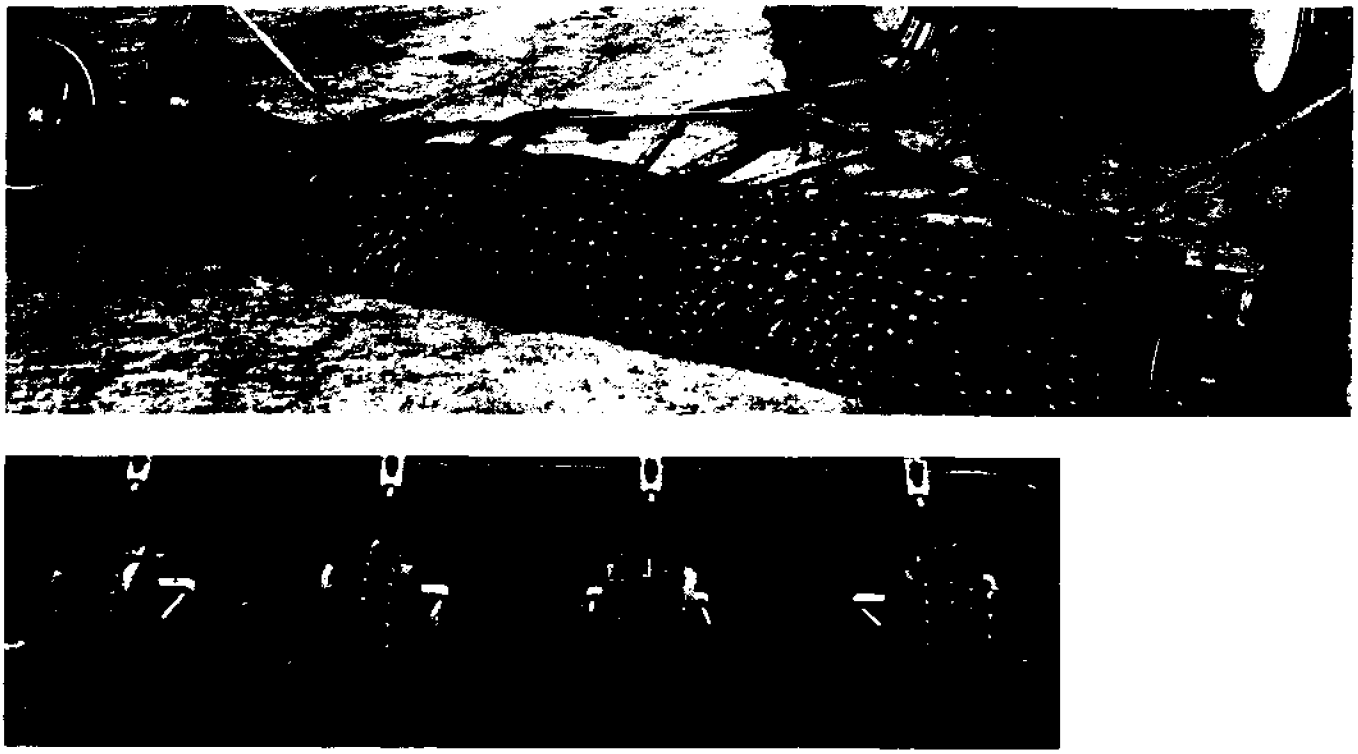


Figure 1-3. Crust-breaking equipment for improving seedling emergence.

crust while soil movement is minimized. Various combinations of inside and outside ring sizes may be used, and units for individual rows are also available. Farmer experience with this type of equipment has generally been good, and crusts can be broken without serious seedling injury. Some farmers in the Yakima Valley of Washington have constructed crust-breakers by welding hardware cloth (one inch mesh) to two metal wheels spaced several inches apart. The unit is placed so that the hardware cloth rolls over the seeded row, breaking the crust over the seedlings. The rotary hoe also has been used for crust breaking, but the action is rather severe and can destroy most of the seedlings. Finger weeders and spring-tooth harrows also have been used. Their success, however, depends on crusting degree and seedling size and vigor. This type of equipment tends to move soil if crusting is severe, so there is danger of pulling up seedlings.

In cotton-growing areas subject to severe crusting, the seeds are often planted in a bed or flat and then hilled over. When the seedlings are developing well, the overlying soil is graded away, just above the seedling crook, thus leaving noncrusted, moist soil for the seedling to emerge through. A similar practice is sometimes used for beans in Idaho.

Other possibilities for achieving emergence through crusts include planting the seeds much thicker than the desired stand, so that some may emerge through cracks or may actually create cracks by group force. Firm soil around and below a seed allows its maximum growing force to be applied to the crust above it. The ideal planter pushes the seed into firm, moist soil and then covers it with the proper depth of loose soil. Seed orientation in the soil at planting is also an important factor in the ability of some seedlings to penetrate a crust. A special planter has been developed to orient beans (Hayden and Bowers, 1974). Additional details are presented in Chapter 2.

Although crusting is generally considered undesirable for crop production, a thick crust does reduce weed emergence, create a warmer seedbed during the day, and offer a degree of frost protection at night. Some effort has been made to utilize these advantages by punch planting, i.e., dropping individual seeds through holes in the crust without otherwise disturbing it. Machines to do this are not yet commercially available, but interest is evident. Other potential advantages of punch planting are discussed in Chapter 2, and an analysis of heat transfer related to soil crusts is given in Chapter 5.

Crust breaking tillage is sometimes used after seedlings have emerged for the avowed purpose of improving aeration. However, seldom will a dry soil crust interfere with soil air exchange. It is only when the crust is very wet that air passage is restricted and aeration problems may develop. This subject is discussed in more detail in the following chapter.

• CHAPTER 2

Modification of Soil Crusts for Plant Growth

David E. Miller and Richard O. Gifford

Surface crusts are a major structural feature of soils in many arid regions. Their properties and manner of formation have been studied for many years and attempts have been made to apply the knowledge gained to rational control of crusting. This application has been difficult because of the problems of isolating factors of crust formation and evaluating their relative contributions. Nevertheless, it is desirable to modify soil crusts, prevent their occurrence, control their rigidity, or even encourage their formation when it would be advantageous.

Probably the most important effect of soil crusts is on emergence and early development of seedlings. Their influence in decreasing or preventing seedling emergence has been illustrated many times (Hanks and Thorpe, 1957; Taylor, 1962, 1966; Ellis, 1967; Frelich et al., 1973; and others). Also, seedlings may be injured by movement of soil during cultivation of a crusted soil. Another important consideration is that soil crusts reduce water infiltration, with a resulting increase in runoff and erosion and reduced water-use efficiencies. A recent example of this problem is the crusting and runoff encountered under modern center-pivot sprinkler systems that have been established on other than sandy soils (Aarstad and Miller, 1973). On one field planted to sugarbeets (a loam soil), about 50% of the applied irrigation water was lost as runoff during of the irrigation season. In some situations, like water harvesting, soil crusts may be beneficial in decreasing water infiltration. Causing runoff from small watersheds to gain additional water on adjacent areas or to increase surface water supplies may be desirable, as pointed out in Chapter 1, and by Hillel (1972).

Soil Crusts and Aeration

Soil crusts have been blamed frequently for poor aeration, and cultivation has been cited as beneficial by breaking up crusts and thus improving aeration. However, Van Bavel (1951), and Domby and Kohnke (1956) show that crusts have almost no effect on aeration unless they are completely impervious or very wet. Sale (1964) found that wet crusts greatly reduced diffusion of gas, but he concluded that crusts influence soil aeration only when wet, and then only if they have few cracks and imperfections. If a small proportion of the soil surface is noncrusted or cracked, diffusion can be quite rapid although most of the surface is sealed with a wet crust. Inasmuch as adequate routes for gas exchange exist through most crusts, especially as they crack upon drying, aeration effects are usually negligible, compared with several more important aspects of soil crusting. However, aeration problems related to crusts may result from the high-frequency sprinkler irrigation systems being developed—especially the center-pivot systems with high application rates and accompanying high waterdrop impact over much of the irrigated area. Crusts formed while the soil is nearly bare may remain wet enough with daily or more freqent irrigation to interfere with gas exchange. The problem will be more prevalent on medium or finer textured soils.

The interference with gas exchange by a wet surface soil is illustrated by the results of Miller and Aarstad (unpublished data, Prosser, Washington). They measured soil-air composition in potatoes and sugar-beet fields sprinkler irrigated daily to replenish either 100% or 75% of evapotranspiration. Carbon dioxide buildup and oxygen depletion were measured and the results are shown in Table 2-1 for two dates. In some plots, carbon dioxide concentrations were more than 8%, and oxygen concentrations were less than 10%. In furrow-irrigated field beans, carbon dioxide accumulation was

usually less than 1%, even during and shortly after irrigation.

Table 2-1. Soil air composition at various depths in Warden fine sandy loam cropped to potatoes and sugarbeets and irrigated daily with sprinklers to replace 100% or 75% of evapotranspiration (ET) during 1973. Each value is a mean for 3 sample sites.

	Potatoes—Sampled August 15			Sugarbeets—Sampled August 24		
	Soil depth—cm					
%	15	30	45	15	30	45
	Irrigated to replace 100% ET					
CO_2	4.1	4.8	3.1	2.7	5.2	6.5
O_2	16.8	15.8	16.9	16.2	13.9	12.8
N_2	78.1	78.4	79.1	80.2	79.9	79.7
	Irrigated to replace 75% ET					
CO_2	0.4	0.7	0.3	0.9	1.2	1.7
O_2	20.7	20.3	21.1	20.3	20.2	19.7
N_2	77.9	77.9	77.6	77.8	77.6	77.6

Reducing Crust Formation

If a soil crust is detrimental, then an obvious solution is to prevent the crust from forming if such prevention is practically possible. Crust formation results largely from aggregate destruction following the impact of waterdrops during rainfall or sprinkler irrigation and from surface saturation by flooding or application of water in excess of the infiltration capacity (see Chapter 1). In agreement with McIntyre (1958a, 1958b), the waterdrop effect is usually considered to be the most important process. However, at the 1972 Symposium on Soil Conditioning (DeBoodt, 1972), several papers were devoted to the process of aggregate breakdown by slaking and explosion during saturation. Lemos and Lutz (1957) state that crusts may form on soil of almost any texture except coarse sands with very low silt and clay. Tackett and Pearson (1965) showed that crusts formed under simulated rainfall had a dense surface layer 1 to 3 mm thick, and the surface was coated with a thin layer of well-oriented clay. The crust was underlain by a more porous structure and the water permeability of this underlying material was about 5 times that of the surface 0 to 5 mm. Epstein and Grant (1967) showed that crusts formed rapidly under rainfall and crust compactness increased rapidly during the first few minutes. Similar results have been reported by Duley (1939), Lemos and Lutz (1957), McIntyre (1958a), and many others. Some soils tend to form thick crusts, as reported by Timm et al. (1971). A sandy loam soil at Shafter, California crusted severely after intense but short rains. When the soil dried, crusts up to 7 cm thick could be removed in large clods. This extreme crust reduced and delayed emergence of potatoes, unless it was kept moist.

Characteristics that make surface soil especially susceptible to crusting are low organic matter, high exchangeable sodium, and high silt content. These are all related to low structural stability, so that soil aggregates are easily broken down under impact of slaking action of water. A dense, massive structure can result, and the soil forms into a hard crust upon drying. Soils high in silt apparently have sufficient particle-to-particle contacts to form strong bonds when the soil dries, thus forming a hard crust. They also have low swelling and shrinking properties, so that the crust does not crack or disintegrate by itself.

Reduction of impact from water drops

Inasmuch as waterdrop impact is a major process in crust formation on bare soils, an effective way to reduce crusting is by reducing this impact. This can be achieved by absorption of the kinetic energy of the falling drop before it strikes the soil, as by surface mulches, or by reducing the waterdrop momentum by reducing droplet size and application rate. The data in Table 2-2 given by Lull (1959) illustrate the wide range in kinetic energy, and thus in compactive force, associated with rainfall of various intensities.

Soil surface cover or mulches reduce the impact of waterdrops on the soil and thus reduce aggregate breakdown and subsequent crust formation. The work of Duley (1939) emphasizes the importance of surface cover on reducing compaction from rainfall, and on maintaining high infiltration rates. He observed that rainfall on bare soil is accompanied by rapid reduction of intake rate as the soil surface structure breaks down and a seal is formed. Covering the soil with burlap or straw during a rainstorm prevented surface soil dispersion and maintained high infiltration rates (Figure 2-1).

Figure 2-1. Effects of removing surface mulches on the intake rate of a sandy loam soil under sprinklers (Duley, 1939).

Table 2.2. Kinetic energy and number of drops for rainfall of various intensities (from Lull, 1959).

Rainfall	Intensity	Median diameter	Fall velocity	Number of Drops	Kinetic energy/area unit time
	cm/hr	mm	m/sec	$h_o/m^2/sec$	joules/(m^2 hr)
Fog	0.013	0.01	0.003	67,425,696	5.9×10^{-7}
Mist	0.005	0.10	0.021	27,018	1.2×10^{-3}
Drizzle	0.025	0.96	4.1	150	2.2
Light rain	0.10	1.24	4.8	280	12
Moderate rain	0.38	1.60	5.7	495	62
Heavy rain	1.5	2.05	6.7	495	3.4×10^2
Excessive rain	4.1	2.40	7.3	820	3.2×10^3
Cloudburst	10.0	2.85	7.9	1,215	3.3×10^3
Cloudburst	10.0	4.00	8.9	440	4.0×10^3
Cloudburst	10.0	6.00	9.3	130	4.4×10^3

Surface mulches of plant residue are effective in reducing crusting and subsequent runoff and erosion (Duley and Kelley, 1939; Borst and Woodburn, 1942; Mannering and Meyer, 1963; Myhre and Sanford, 1972; and others). Larson and Allmaras (1971) mention that close-growing crops, such as grasses, provide nearly complete cover and usually prevent serious crust formations. Variations in plant populations and crop geometries offer a means of altering the area of soil surface exposed to waterdrops.

In a study of management practices to reduce runoff under center-pivot sprinkler systems, Aarstad and Miller (1973) compared a surface mulch of alfalfa, incorporation of alfalfa to a depth of 8 to 10 cm, small basins in a furrow, and a control. Although the basins were most effective, the surface mulch and the incorporated alfalfa markedly reduced runoff. These results are given in Table 2-3. Yields of sugarbeets and potatoes were increased as a result of reducing runoff and thus increasing the plant's water supply. In general, keeping plant cover over the ground will reduce crusting and maintain infiltration rates.

A number of other mulch materials have been shown to be effective in eliminating crusting by absorbing the raindrop energy and by not being subject to crusting themselves. Bennett et al. (1964) obtained increased emergence of cotton on a Greenville fine sand loam through use of various mulches. On bare soil, emergence was 10%; black plastic cover gave 78%; and asphalt emulsion, or vinyl resin emulsion resulted in at least 50% emergence. Qashu and Evans (1967) used coke to decrease crusting of soils. Surface soil under

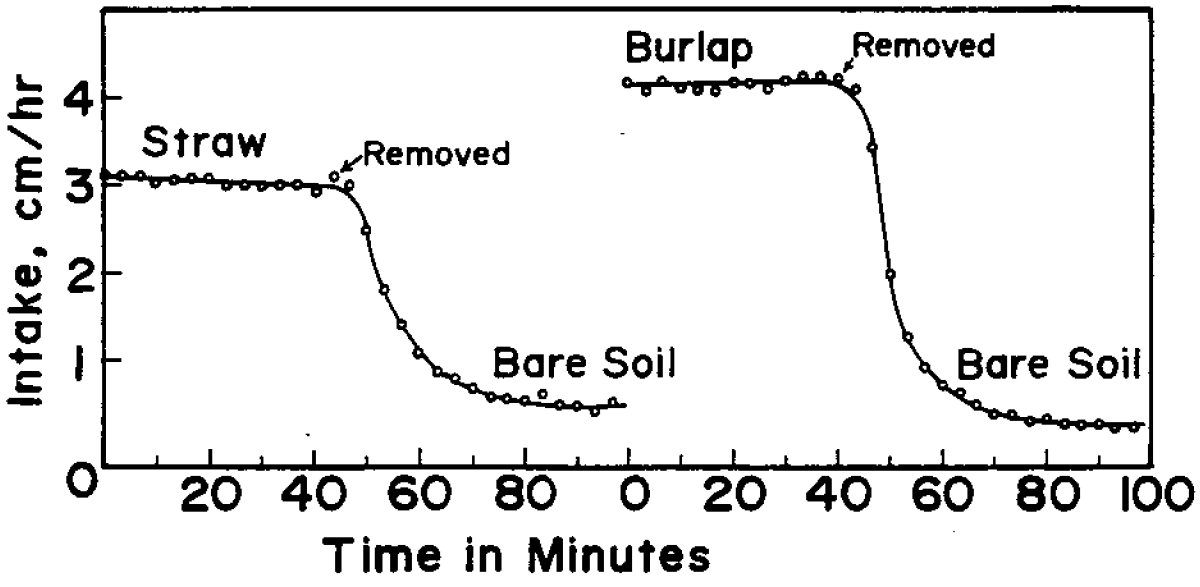


Table 2.3. Effect of various soil management practices on percent runoff from center-pivot sprinkler systems (from Aarstad and Miller, 1973).

	Circle 1 (Beets)		Circle 2 (Potatoes)	
Treatment	Measurements	Runoff	Measurements	Runoff
	No.	%	No.	%
Control	28	11	26	16
60-cm basins	2	1	3	1
11 metric T/ha hay inc.	8	2	11	2
4.5 metric T/ha hay mulch	8	5	11	2

	Circle 3 (Potatoes)		Circle 4 (Beets)	
Treatment	Measurements	Runoff	Measurements	Runoff
	No.	%	No.	%
Control	24	17	22	41
60-cm basins	5	1	8	1
11metric T/ha hay inc.	12	1	15	6
4.5 metric T/ha hay mulch	12	3	19	30

the coke mulch remained moist for 2 to 3 weeks after irrigation and did not crust, whereas bare soil was dry and crusted within 2 to 3 days. In addition to the effect on crusting, mulches such as coke, asphalt, or plastic give more favorable soil environment by increasing moisture and temperature. Ellis (1967) evaluated asphalt emulsion and sand or perlite trailed in a small groove over the seeded row on crusting and emergence and growth of direct-seeded tomatoes. The perlite was most effective. Applied in this matter, 0.28 m^3 of perlite will treat 1 hectare seeded in 91-cm rows. Ririe and Huffman (1969) planted lettuce seeds in 1.3-cm-square depressions and covered the seeds with soil sprayed with asphalt emulsion, stabilized vermiculite, or petroleum coke. After being sprinkled with 2.5 cm of water, the bare soil crusted and restricted emergence, but the mulched soil did not crust. The vermiculite and coke were especially effective. Lettuce emerged through them 3 days earlier than from bare soil, and emergence was increased from 30-40% to about 80-85%. Petroleum mulch increased emergence to about 50%. Similar results have been obtained with sugarbeets (Ririe and Hills, 1970). Corey and Kemper (1968) found that a 1-cm layer of pea gravel absorbed most of the impact of raindrops and prevented excessive crust formation. Infiltration on soils with good aggregate stability remained above 3 cm per hour when a gravel layer was present. Although not normally economically feasible, a gravel layer may be applicable for recharging groundwater at permanent sites or for high-value plants.

Waterdrop momentum and compaction energy increases with drop size and rate of application (Table 2-2). Although these factors are not controllable for natural rainfall, a large degree of control is possible with modern sprinkler irrigation systems through manipulation of pressure and nozzle size (Kohl, in press). As may be expected from the values in Table 2-2, light irrigations with small droplets will compact soil much less than high application rates with large drops. Sale (1964), and Sale and Harrison (1964) quote studies that show that waterdrops 5 mm in diameter have about 25 times as much kinetic energy as the same total volume of water falling in 0.5-mm drops, all at terminal velocity. Their work also showed that large waterdrops caused much more severe crusting and reduced emergence than small drops. Lyles et al. (1969) observed that 10 minutes of rainfall at 5.6 cm/hour was as destructive to soil surface structure as 90 minutes at 1.6 cm/hour, even though the latter applied 2.5 times as much water. Moldenhauer and Kemper (1969) observed that infiltration decreased and runoff increased as cumulative waterdrop energy increased (water was applied at a given rate and the cumulative energy was varied by length or number of irrigations). The decrease in infiltration was associated with increasingly severe crust formation. The larger aggregates tended to keep the soil surface from being completely covered with a severe crust, because the displaced material washed down into the depressions between aggregates, and infiltration remained higher than with the smaller aggregates (Figure 2-2). Also, their work showed that when a crust formed, soil fragments below the crust remained nearly intact. As with plant residue or other covers, when the raindrop energy is absorbed at the surface, soil aggregates below do not disintegrate.

Erosion and infiltration studies conducted in the Midwest with natural or simulated rainfall indicated that as rainfall became more intense, surface soil aggregate deterioration increased, infiltration decreased, and erosion intensified (Parr and Bertrand, 1960).

Effect of degree of wetting

The rigidity of a soil crust is affected by the degree to which the soil is wet before drying (see Chapter 4).

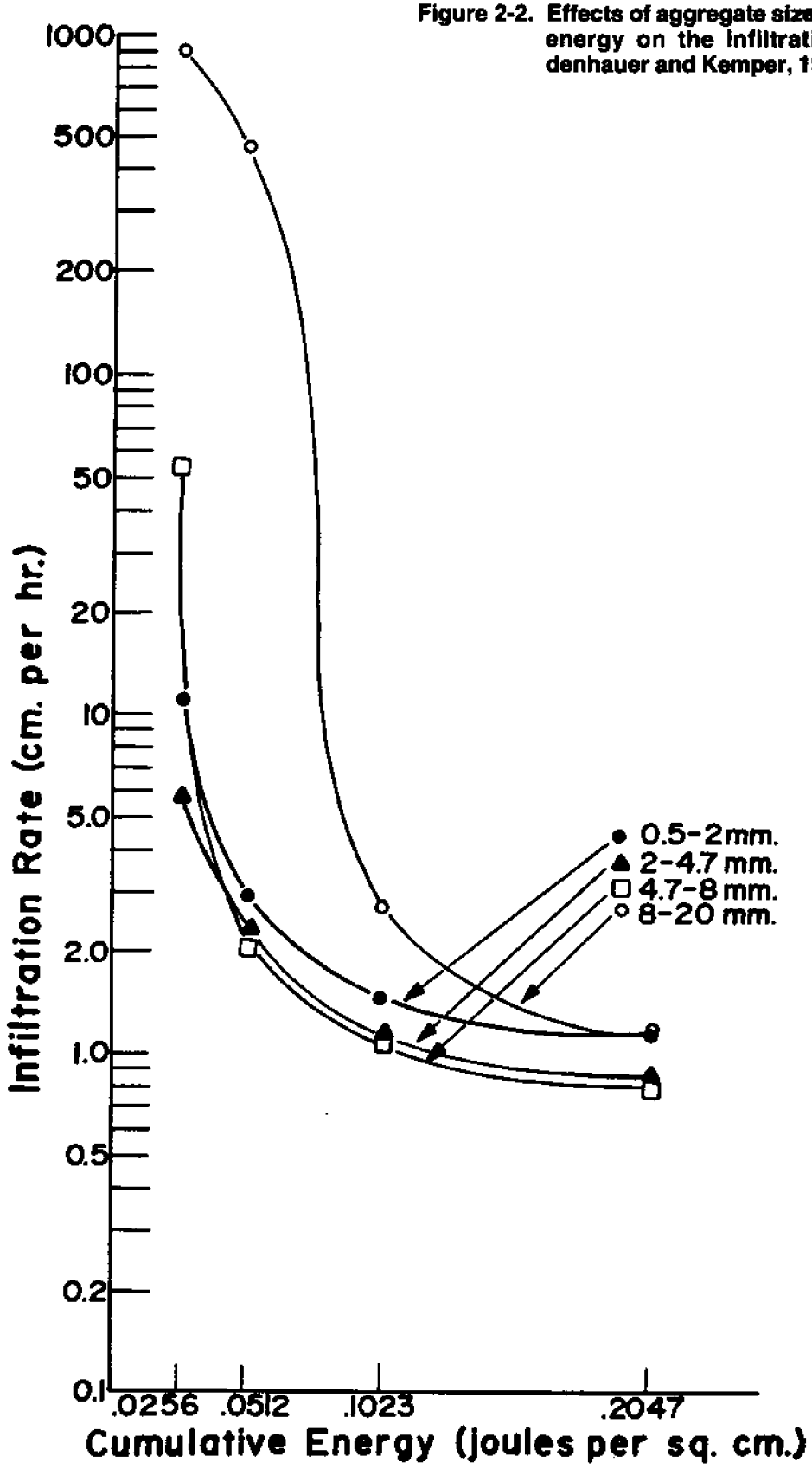


Figure 2-2. Effects of aggregate sizes and raindrop energy on the infiltration rate (Moldenhauer and Kemper, 1969).

Modulus of rupture of soil briquets wet to saturation under 1.5 cm of water pressure may be nearly twice as great as for briquets wet to values only slightly less than saturation. The strength of a crust forming in an irrigation furrow is greater just below the water line, where the soil has been saturated, than just above the water line, where there has been a slight suction. Crusting under sprinklers is much less severe when water is applied at rates less than the infiltration capacity, so that ponding does not occur, as compared with heavier application rates that cause ponding. The waterdrops destroy soil aggregates more when the soil is saturated than when it is not, and the higher application rates usually mean larger drop size and thus greater impact and destructive force. However, surface irrigation by ponding may cause more severe crusting than sprinkling, as illustrated by the photographs in Chapter 5 (Figure 5-3).

Effect of water quality

The quality of irrigation water, as well as the method and rate of application influence the formation and hardness of a crust. The sodium adsorption ratio (SAR), a measure of the sodium hazard, is the most important water property related to crust formation. Some of the sodium salts in the water are concentrated at the soil surface by evaporation. If enough sodium is adsorbed by the surface soil, it will disperse when rewet by irrigation or rain. A crust may then form without any mechanical energy input to rearrange and compact the soil particles. Not all sodium-affected soils form crusts. Some with swelling clays are self-mulching in that the surface layer shrinks and cracks into fragments as it dries. The probable effect of irrigation water with a high SAR in forming crusts in a given soil may be estimated by wetting samples of the soil in a modulus of rupture test with a solution of 50 g/1 of Calgon (sodium hexametaphosphate). This solution precipitates the calcium ions, allowing the sodium to adsorb on the soil, simulating the conditions that result from sodium salt accumulation at the soil surface (see Chapter 4).

Reduction of crusting tendency

Over the past 20 years, a number of attempts have been made to reduce the crusting tendency of soils or to encourage formation of a low-strength crust by the use of chemical additives, crop rotations, and residue management. The synthetic polyelectrolyte soil conditioners, developed in the early 1950's, spawned a rash of research directed toward increasing aggregate stability and reducing soil crusting, among other things. Pertinent research work has been reviewed by Harris et al. (1966). Gardner (1972) recently reviewed the history of soil conditioner research and reported that over 200 publications were made on the subject from 1951 to 1963. Although soil conditioners were very effective and long-lasting, their cost was prohibitive for agricultural use, so they were never used on a field scale. Typical of the results obtained are those of Allison (1956), who treated Pachappa loam with VAMA[1] and HPAN[2] at the rate of 0.1% by weight for the upper 15 cm of soil. The treatments resulted in large increases in aggregate stability, up to 10-fold increases in infiltration rate, reduced modulus of rupture, and increased emergence and yield of corn. Sodium was removed from the surface 15 cm of soil about twice as fast from the treated plot as from the control plots. He stated that the treatment of poorly aggregated soil with synthetic soil conditioners, especially high sodium soils, invariably greatly improved aggregation and aggregate stability, permeability, infiltration rates, aeration, tillability, and resistance to crust formation and erosion. Similar benefits from use of soil conditioners have been reported by Hedrick and Mowry, 1952; Martin et al., 1952; Allison and Moore, 1956; Bennett et al., 1964; and many others. Doyle and MacLean (1959) found that waste sulfite liquor solids were much less effective than HPAN and VAMA in increasing aggregation.

Interest in soil conditioning agents has been revived recently, and symposia on the fundamentals of soil conditioning were held in Belgium in 1972 (DeBoodt, 1972), and in the United States in 1973 (1973 meetings of American Society of Agronomy). Moldenhauer and Gabriels (1972) discussed several reasons why interest is again high: (1) Early work was directed toward agriculture, which has a low profit margin per unit area of land. Now other uses are visualized, such as erosion control on construction projects, stabilization and seeding or roadcuts, military sites, etc., which can justify much more expenditure for soil stabilization than can agriculture. (2) Many new products are available, with a wider range of usefulness. (3) A need and demand for the product exists.

Because breakdown of soil aggregates under the impact of raindrops or slaking action of water is a major part of soil crust formation, practices that increase aggregate stability will usually decrease crusting. Modulus of rupture has been used also as a measure of crusting tendency. Law et al. (1966) treated two montmorillonite soils with anionic, cationic, and nonionic surfactants and evaluated their effect on aggregate stability, capillary rise, and modulus of rupture. The anionic materials had little effect on soil physical properties, but greatly decreased the surface tension of water in the soil. Cationic materials increased aggregate stability and decreased modulus of rupture, but also made the soil hydrophobic. Nonionic surfactants, applied at a rate of 1% by weight, increased aggregate stability without significantly affecting soil wettability. Although the nonionic materials were beneficial, their use is questionable because of their high cost.

Hexadecanol applied to the soil has been shown to have pronounced effects on soil aggregation, water in-

[1]The copolymer of vinyl acetate and the partial methylester of maleic acid.
[2]Hydrolyzed polyacrylonitrile.

take rate, evaporation, and crust strength. Myhrman and Evans (1969) reported that modulus of rupture was reduced 65% in a sandy loam soil and 57% in a silt loam by addition of 0.4% by weight of powdered hexadecanol. Olsen et al. (1964) also observed that hexadecanol produced larger, more stable soil aggregates. Several people have shown that hexadecanol or mixtures of fatty alcohols can reduce evaporation from soil (Aubertin and Gorsline, 1964; Olsen et al., 1964; and Kolp et al., 1966). Moldenhauer and Gabriels (1972) reported that polyvinyl alcohol reduced water runoff and soil erosion in soil cropped to corn. Armbrust and Dickerson (1971) showed this material was effective in controlling wind erosion.

Ahuja and Swartzendruber (1972) studied the effects of Portland cement (a mixture of calcium disilicate, tricalcium silicate, tricalcium aluminate and tetracalcium alumino ferrite) to a silt loam soil. Rates of 0.415, 0.95, and 1.90% by weight were used at various times of moist curing. Water stability increased with both the rate of application and duration of moist curing. Saturated conductivities were also increased by the cement.

Robbins et al. (1972) sprayed dilute phosphoric acid along rows seeded to sugarbeets in calcareous Portneuf silt loam. An application of 68 kg P/ha as dilute phosphoric acid reduced crusting by increasing aggregate stability, increased sugarbeet seedling emergence, and also provided the phosphorus needed by the crop. Their explanation for the beneficial effect on structure is that the acid dissolved Ca and Mg carbonates, and the free cations probably reacted with PO_4^{-3} to form slightly soluble phosphates that acted as cementing agents. Johnson and Law (1967) obtained similar results by applying sulfuric acid to soil, but the material was difficult and hazardous to use. Application of phosphorus, as phosphoric acid, or as monocalcium phosphate, reduced modulus of rupture in 3 red-yellow podzols in North Carolina (Lutz and Pinto, 1965). Conversely, use of fertilizers containing ammonium or sodium has caused soil dispersion, crusting, and reduced permeability (Aldrich et al., 1945; Fireman et al., 1945; Fox et al., 1952).

Kemper and Noonan (1970) showed that calcium and sodium added to the surface of a crust-prone soil have important effects on infiltration. Sodium decreased infiltration because it allowed the aggregates to disperse. Calcium prevented the dispersion and made the surface more stable (Figure 2-3). A cheap way to decrease surface crusting and increase seedling emergence in high sodium soils may be to apply a narrow band of gypsum over the seeded row, using approximately 100 to 200 kg/ha.

Although some chemicals will reduce crusting, their cost is usually prohibitive for agriculture. Except for phosphoric acid and gypsum, such chemicals are not promising as economical ways to eliminate or reduce soil crusting, except on very high-value crops.

Kemper and Koch (1966) showed that aggregate stability and organic matter content are closely related. Unfortunately, under row crops it is difficult to permanently increase organic matter in soils, because of its rapid decomposition. Many studies have been conducted on the effect of various cropping practices and sequences on soil physical properties, including aggregate stability and modulus of rupture. If these two properties are taken as reliable measures of a soil's tendency to crust, it seems probable that crusting can be reduced by cropping practices. Physical properties of soils have been improved, including increased aggregate stability, when a cropping sequence has included alfalfa or sod crops, as opposed to continuous row cropping. The benefit is greatest the year that row cropping is again started, but may be measureable for several years (Wisniewsky et al., 1958; Mazurak et al., 1954; Patrick et al., 1957; Barber, 1959; and others). Chapter 3 discusses, in detail, the role of organic matter in binding particles into stable aggregates. The relation between cropping practices and soil aggregation has been reviewed by Harris et al. (1966), who concluded that crops that provide minimal vegetative cover, supply little readily decomposable organic material to the soil, and require extensive cultivation are least able to maintain optimum soil tilth.

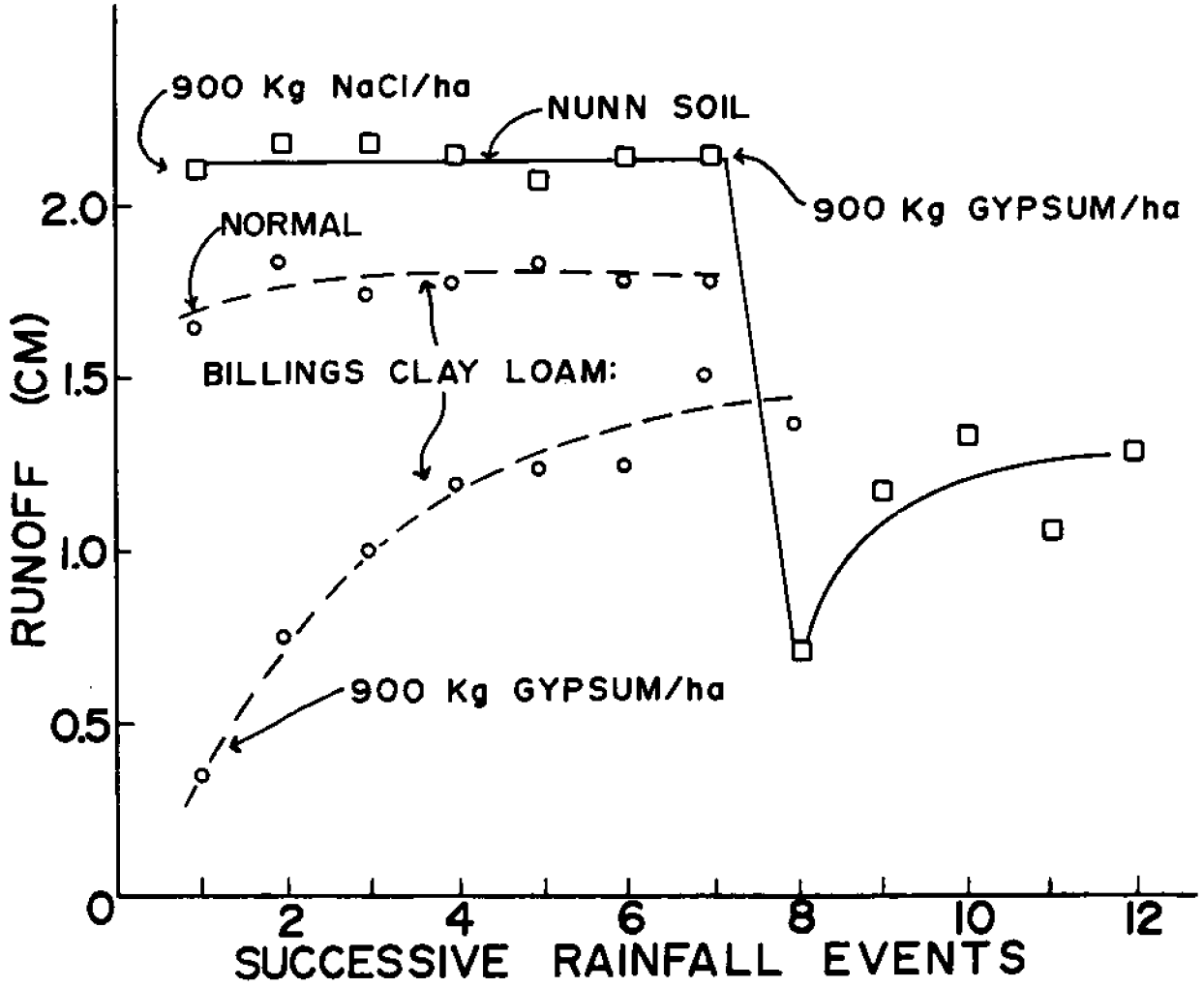
As an example of the effect of cultural history on crusting, Evans and Buol (1968) used thin sections from irrigation furrows to show that continuous cotton resulted in a rigid crust nearly devoid of large pores. When cotton followed 3 years of alfalfa, the crust was more porous and less rigid. Modulus of rupture was 2.4 bars for continuous cotton, and 1.8 when cotton followed alfalfa. Miller and Kemper (1962) increased aggregate stability of two soils by incorporation of alfalfa. Miller and Aarstad (1971) observed a marked increase in infiltration rate in furrows with straw mixed into the surface 15 cm. The soil also was more stable and friable than the control.

Encouraging Emergence through Crusts

Crust strength and cracking

Taylor (1971) has reviewed what happens when an elongating shoot strikes a surface crust. If the shoot encounters a crust that is too strong to break through, it may grow horizontally and sometimes emerge through a crack. Thus, two effective ways to improve emergence through crusts would be to decrease the strength of crusts that have formed, or to increase the cracking as it forms. The strength of a given crust decreases rapidly as water content increases (Carnes, 1934; Hanks and Thorpe, 1956, 1957; Morton and Buchele, 1960; Bennett et al., 1964). Marsh and Johnson (1967) reported that in lettuce plantings under desert conditions, daily irrigations are necessary to obtain good stands—sprinkling is recommended. Timm et al. (1971) found that a severe crust, 7 cm

Figure 2-3. Effect of gypsum and NaC1 on the runoff from 2 soils subjected to rainfall events of 3 cm of rain in one hour preceded by drying (Kemper and Noonan, 1970).



thick, did not injure potatoes when it was kept moist by sprinkling. Furrow irrigation also can be used to keep a crusted soil moist, but the amount of water applied is much more difficult to control and danger of overirrigating exists, especially at the top of a field. Details concerning irrigation for crust softening are given in Chapter 1.

Seedlings located near a crack are more likely to emerge than those that are forced to penetrate a crust. If cracking intensity can be increased, or cracks formed over a seed, then emergence should be increased accordingly. Using metal probes to simulate seedlings, Morton and Buchele (1960) showed that low emergence energy was required when cracks form. Johnson (1962) demonstrated that cracking could be controlled by wheat row geometry in Pullman clay loam. When a row of wheat was omitted, cracks formed where the row was omitted were twice as wide as those formed within the uniform wheat stand. Hemwell and Scott (1962) used a fracturing agent (4-tert-butylpyrocatechol) applied over the seeded row to increase emergence of radish seedlings through increasing fracture lines in the soil surface. They obtained 90% emergence with the chemical compared with 45% emergence on the control. They found that the reduction in soil strength per unit of chemical was a direct function of the cation exchange capacity of the soil. Bennett et al. (1964) found that a soil fracturing agent increased emergence as much as did asphalt emulsion, and nearly as much as black plastic cover. Perlite, trailed in a 0.6-cm groove over direct-seeded tomatoes, resulted in a fracture line developing over the

seeded row (Ellis, 1967). The mechanics of crust cracking have been studied and a general theory is presented in Chapter 4.

Another way of bypassing a crust was suggested by Cary (1967b, 1968) who showed that a number of species could be established by placing single seeds in holes punched through a soil crust. Seeds could be planted deep enough to be in moist soil, and yet not have to encounter any resistance to emergence. Bean plants planted 15 to 20 cm deep grew well. He suggests this method for areas where a stable crust can be formed and where heavy, erosive rains are not likely during germination and emergence. However, holes could be backfilled with noncrusting material (sand, vermiculite, stable aggregates) where danger of their becoming filled exists. Heinemann et al. (1973) have worked on experimental planters for placing single seeds in holes punched in the soil.

Emergence ability of seedlings

A number of methods have been suggested to improve a seedling's ability to penetrate a crust. A single seedling may be unable to go through a crust, whereas a group of seedlings may exert enough thrust to break a crust and emerge. Ray et al. (1952) indicated that, under crusting conditions, cotton seedlings at heavier rates of planting have a crust-breaking push that will improve chances of obtaining more and faster emergence. Edwards (1966) concluded that a satisfactory stand of cotton could be obtained in crusted Houston clay by planting 3 seeds per hill, whereas single seeds were unable to emerge. Hillel (1959) suggested using large seeds of different plants to help rupture crusts for smaller seeded plants. However, with present emphasis on mechanization and reduced labor, planting excess seeds or unwanted species is not satisfactory for many crops because of the expense of postemergence thinning.

According to Barley and Greacen (1967), if a seed is planted in loose soil and the seedling meets a soil crust, the shoot may push the seed deeper into the soil rather than emerge through the crust (quoting Carnes, 1934). Also, if a shoot lacks sufficient radial support, it will more likely be bent when it contacts a crust. Taylor (1971) quotes Chambers (1962) and Arndt (1965a, 1965b) as indicating that lateral anchorage is very important in allowing a shoot to exert its potential thrust for crust penetration. Thus, some compaction of soil around a seed should be beneficial. Carnes (1934) recommended packing soil to give the seedlings a firm foundation.

Stout et al. (1956) found that compressing soil over sugarbeet seeds at pressures greater than about 0.3 bars reduced seedling emergence, while a slight pressure of 0.1 to 0.3 bars were beneficial. Although Stout et al. (1961) also observed that compacting soil over seeds reduced emergence, they found that, in a laboratory test, emergence was increased by applying pressure at the seed level and then covering the seed with loose soil. From their work, they concluded that planters for sugarbeets, corn, and beans should be designed to pack the soil below the seed level, press the seed into the compact soil, and cover the seeds with loose soil.

Jones et al. (1956) used such a seeder with cotton. A rubber presswheel packed the seed into the bottom of a seeder furrow behind a narrow shielded furrow opener. The seeds were covered with loose soil. Cotton seedling emergence was greatly improved by this seeding procedure as compared with conventional methods.

In the field, a 4-way benefit should result from the seeding procedure described above: (a) The seed is pressed into moist soil, thus encouraging adequate moisture supply for germination; (b) evaporation from the soil is discouraged by the layer of loose soil over the seed; (c) adequate aeration to the seed is maintained; and (d) the soil surface should resist crusting much better in a loose condition than when it is compacted. With the exception of cotton, this planting technique apparently has not been evaluated in the field, and most commercial seeders pack the soil over the seed with a surface packer wheel.

Bowers and Hayden (1972) found that bean seeds planted with the hypocotyl end down produced fewer seedlings than those planted with the hypocotyl end up or laid flat. The adverse effect of the hypocotyl-end-down orientation was attributed to the required seed rotation before emergence. Little information is available on orientation for other plant species, but Hayden and Bowers (1974) have developed a planting shoe to properly orient bean seeds.

Plant species vary in the amount of force they can exert in breaking through a crust. Williams (1956) measured the emergence force of small-seeded legumes. He gives median emergence forces as:

Alfalfa	1.5×10^4 dynes
Crimson clover	2.3 " "
Rose clover	2.4 " "
Subterranean clover	5.9 " "

Seed weight and emergence force were closely correlated ($r = 0.999$).

Gifford and Thran (1969) developed a special transducer to measure emergence force of seedlings. Pregerminated seedlings were placed in the apparatus, and emergence force was recorded for 7 days. They reported maximum emergence forces as follows:

Lima beans	30.4×10^4 dynes
Corn	24.0 " "
Cucumber	15.7 " "
Cotton	5.9 " "
Radishes	4.2 " "
Tall wheatgrass	0.6 " "

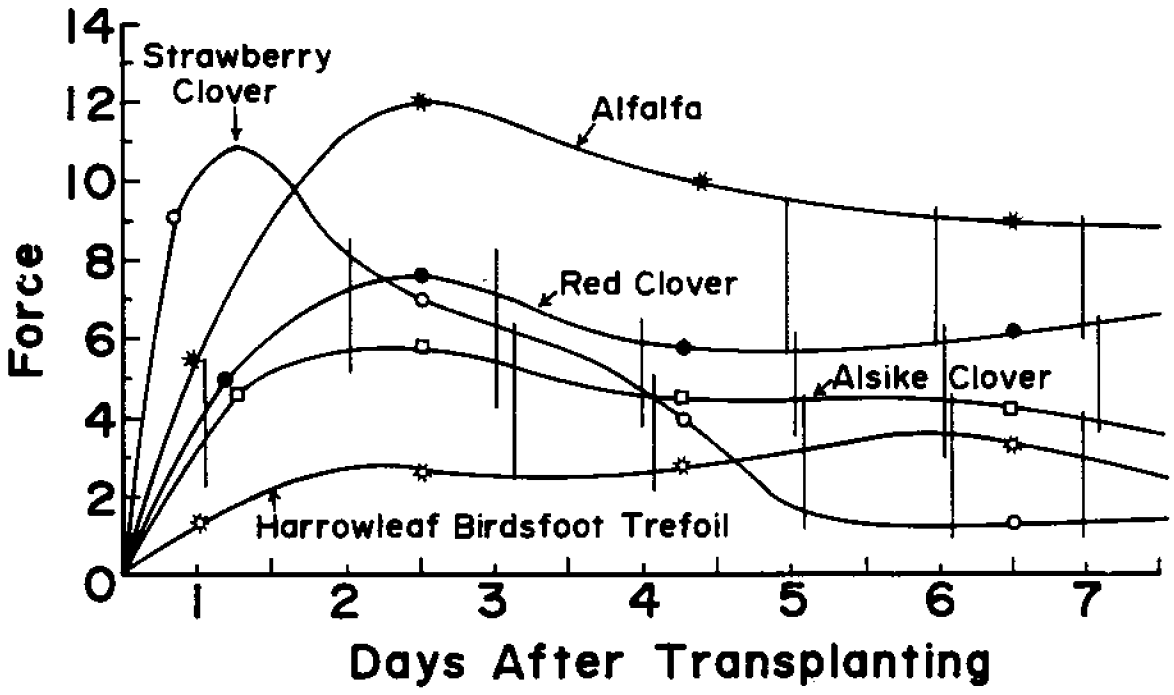
These data also illustrate the correlation between seed size and emergence force.

With this same equipment Jensen, et al. (1972) measured emergence force of forage seedlings. An example of their data is shown in Figure 2-4. Alfalfa exerted higher emergence force for the first 4 days after transplanting than the other species studied. Strawberry clover had the fastest rate of increase in emergence force, while birdsfood trefoil had the slowest rate. Again, emergence force and seed weight were closely correlated ($r = 0.91$). In later work, Frelich et al. (1973) showed that 6 grass species differed greatly in their ability to penetrate nonporous wax crusts. Pubescent wheatgrass and smooth bromegrass were most affected by crust hardness; tall wheatgrass was least affected. The data from these two studies also indicate that decreasing osmotic potential or increasing sodium absorption ratios delays the time of maximum emergence force. In a field situation, this delay could result in additional crust strength before emergence as the soil surface dries out.

Taylor (1962) also has indicated differences among species in reaction to crust hardness. He showed that guar was less affected by crusts than wheat or grain sorghum.

In addition to variation in thrust among species, there are large variations in the conditions required for germination and emergence. Lettuce has a narrow optimum temperature range for germination and has a preemergence period of 10 days or more. Barley is less sensitive to temperature and emerges within 3 or 4 days after planting. Sugarbeets are usually planted in smooth, bare soil in early spring when rains are likely, and require 2 to 3 weeks for emergence under conditions that favor crust formation. Potatoes require several weeks for emergence, but they can usually penetrate a thick crust. Beans and corn are planted in relatively warm soil, emerge within a week, and both have high crust penetration ability. Thus, when a choice is compatible with the farming operations, possibly a species may be selected that is more likely to survive in a crusting soil. Such selections will undoubtedly be limited, since species selection is usually made by criteria other than ability to penetrate a soil crust.

Figure 2-4. Relative force exerted by 4 kinds of growing seedlings with vertical lines indicating significant differences at the 5% level (Jensen et al., 1972).



• CHAPTER 3

Bonding Mechanisms for Soil Crusts:

PART I.

Particle Surfaces and Cementing Agents

Goro Uehara and Rollin C. Jones

Soils consist of particles which range in size from those which measure in fractions of a micron to those which are readily visible to the naked eye. Were it not for the fact that these particles are bound together so that they act in unison with neighboring particles, soils would behave in a manner quite unlike those with which we are familiar. In fact, in the absence of binding agents it is doubtful whether soils as we know them could exist for very long.

A need to study and understand the forces and agents which bind soil particles has been a compelling one for soil scientists, for soil behavior probably depends as much on this single factor as any other. Historically, research on this topic has taken the form of identifying and relating a number of soil constituents to soil aggregation and ultimately to soil tilth. Those factors which are known to affect soil structural stability include such things as the mineralogy of the layered silicates, texture, the composition of sorbed cations, and the concentration of various organic substances, silica and sequioxides. Other variables, such as pH and liming, have also been examined, but they are intercorrelated with each other and to the composition of the exchangeable cations.

Important as this problem may be, no substantial breakthrough in this subject matter area has occurred beyond the empirical and somewhat ambiguous relations which have been shown to exist between soil physical properties and the factors listed above. There are several review articles which cover the topic adequately (Martin et al., 1955; Greenland, 1965a, 1965b; Harris et al., 1966). These reviewers place greatest emphasis on organic matter, possibly because organic matter content and composition can be manipulated to a greater degree by management practices, and because it improves soil productivity with greater consistency than any other variable. In the following sections, this same problem along with some newer information will be examined and discussed with special reference to soil crusts.

Mineral Surfaces

Charge characteristics

Colloidal chemistry is fundamentally surface chemistry. Double layer theory, presently the most useful model for describing colloidal behavior, treats colloids as being of the constant surface charge, or constant surface potential (variable charge) type. Both types can be described by the Gouy-Chapmann double layer equation:

$$\sigma_0 = \left(\frac{2n\epsilon kT}{\pi}\right)^{1/2} \sinh \frac{Ze}{2kT} \Phi_0 \qquad [1]$$

where: σ_0 = surface charge density
n = concentration of equilibrium solution
ϵ = dielectric constant of the medium
k = Boltzmann constant
T = absolute temperature
Z = valence of counter ion
e = charge of electron
Φ_0 = surface potential

For layered silicates such as montmorillonite, σ_0 arises from ion substitution in the interior of crystal lattices. Therefore σ_0 is a constant and independent of the type and concentration of electrolyte in the soil solution. Swelling pressures which develop between clay plates during irrigation can be controlled and manipulated by altering electrolyte concentration (n) and counter ion valence (Z).

In colloids of the constant surface potential type, changes in electrolyte concentrations and counter ion valence result in changes in σ_0 if Φ_0 is held constant. By holding the activity of the potential determining ions

constant, Φ_0 can be held constant. The most important potential determining ions in soil solutions are H^+ and OH^-. The relation between Φ_0 and the potential determining ions is

$$\Phi_0 = \frac{RT}{F} \ln \frac{H^+}{H_0^+} \quad [2]$$

where: R = gas constant
T = absolute temperature
F = Faraday constant
H^+ = hydrogen ion activity
H_0^+ = hydrogen ion activity at the zero point of charge

The amorphous gel-coatings shown in Figures 3-1 to 3-8 most probably behave as constant surface potential colloids. For soil minerals with amorphous coatings, σ_0 and $\Phi_0 = 0$, when $H^+ = H_0^+$. In this condition, the soil colloids are flocculated and crusting rarely occurs. In oxidic soils of the tropics, $H^+ = H_0^+$ between pH 4 to 6 (Van Raij and Peech, 1972; Keng and Uehara, 1973). Since soil pH also falls in this range, crusting is rarely a problem in these soils.

In crusting soils of the arid and semi-arid regions, amorphous silica is most likely the cementing agent (see Figures 3-4 and 3-7). For silica, $H^+ = H_0^+$ near pH 3 (Tardos and Lyklema, 1969). For these soils, pH is generally neutral or alkaline. At these pH's, $H^+ << H_0^+$, σ_0 is negative, and Φ_0 takes on large negative values. Each 10-fold increase in H^+ (one pH unit) above the zero point of charge lowers Φ_0 by -59 mV. For silica, σ_0 increases sharply when soil pH exceeds the pH at the zero point of charge by 4-5 units. In fact, at high pH's the surface charge density of silica (and other oxides) can exceed that of montmorillonite by several times (Breeuwsma, 1973).

Crystal Imperfections

Surface imperfections or dislocations may act as active points for adsorption and even sites for nucleation. Beutelspacher and Van der Marel (1968, p. 267) show an electron micrograph of rod-like ß-ferric-oxyhydroxide growth on surfaces of the mineral pyrophyllite. They suggest that crystal nucleation of the iron oxide occurs at active points on the surface. This type of evidence suggests that even surfaces of low charge density may play an important part in bonding between neighboring particles.

Jones (1970) has found a montmorillonite whose surface was coated with microcrystallites of feldspar. Although each individual feldspar crystal was too small for electron diffraction analysis, he was able to obtain a diffraction pattern which indicated that all crystallites were oriented in the same cyrstallographic direction. Jones identified the feldspar as a calcium feldspar and theorized that it was authigenic in origin.

Surface coatings

Beilby (1921) is credited with describing a film on highly polished surfaces which appeared to flow and cover scratches and pits. This film or layer is known as the Beilby layer. The Dictionary of Mining, Minerals, and Related Terms (Thrush, 1968) defines the Beilby layer as a "flow layer resulting from incipient fusion during polishing mineral surface, and therefore not characteristic of true lattice." This definition was credited to Shipley (1945): "The mirrorlike surface layer, on all well-polished stones other than diamond, which seems to be caused by fusion of tiny surface projections. In corundum and quartz this layer is crystalline, in zircon and spinel it is amorphous and pits more easily than other stones."

Clelland and Ritchie (1952) have attempted to relate high solubility layers on silicious dusts to the Beilby layer. These workers were primarily interested in relating surface coatings on silicious dusts to silicosis. Gibbs et al. (1953) have made estimates of the thickness of this layer on quartz, and arrived at values ranging from a low of 200-300 Angstrom units by solubility measurements to a high of 1100-1500 Angstrom units by means of differential thermal analysis.

The occurrence of amorphous films on soil minerals has been alluded to by several workers. Fields and Williamson (1955), for example, proposed that positively charged amorphous alumino-silicate might exist as surface coatings on clay minerals. They, however, suggested that these coatings would consist of ultrafine particles beyond the resolving power of their electron microscope.

An electron micrograph of finely particulate allophane occurring as a coating on an illite crystal has been published by Mitchell et al. (1964). Follett et al. (1965), after studying the amorphous inorganic material in the clay fraction of two Scottish soils, concluded that most of the amorphous material removed by alkali must have been present as coatings, and that these coatings served to cement primary particles into ill-defined aggregates. Raman and Mortland (1969) also suggest that amorphous coatings (Beilby layers) can alter behavior of soil clays. The effect of amorphous coatings on the quantitative analysis of the finer clay minerals has been also cited by Van der Marel (1966).

The term Beilby layer probably is used incorrectly when used to describe surface coatings on soil minerals and should be restricted to surface films associated with polished surfaces. However, the nature of vitrous coatings on polished surface can be helpful to soil scientists in understanding naturally occurring coatings on soil particles.

The first conclusive evidence for the existence of amorphous coatings on soil clay minerals was presented by Jones et al. (1969, 1973). Through high resolution electron optical examination of kaolinite flakes separated from an oxisol, they were able to see coatings ranging in thickness from 125-400 Angstrom units.

Figure 3-1. Amorphous gel-coatings on halloysite.

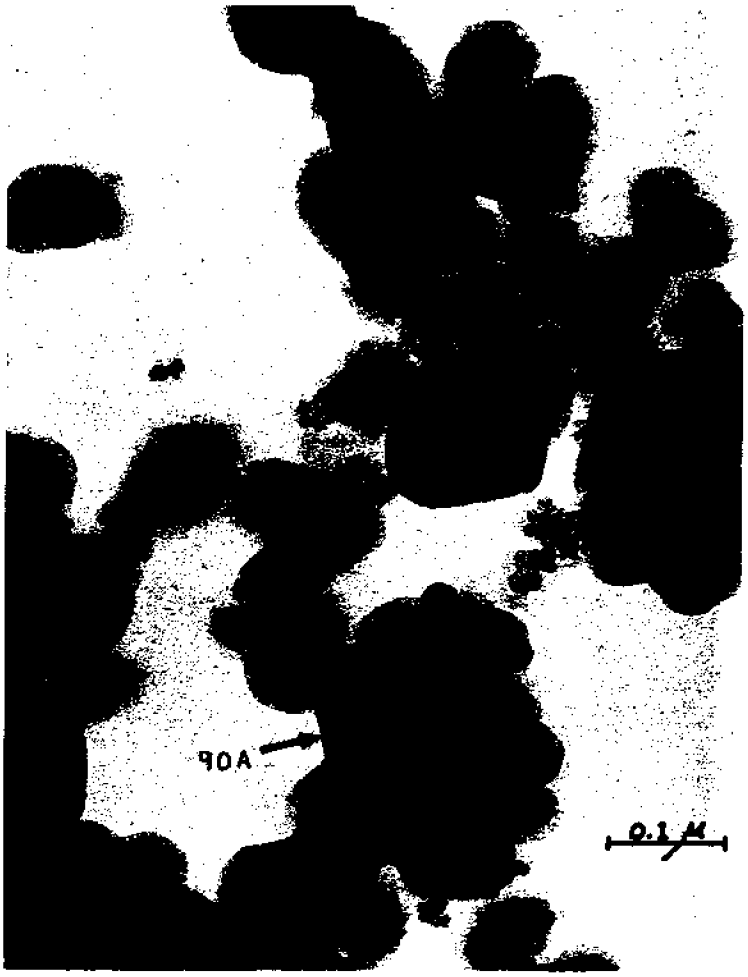


Figure 3-2. Amorphous gel-coatings on kaolinite particles. The raspberry-like objects are poorly crystalline to amorphous iron oxide particles. They represent the readily reducible, extractable free iron oxides.

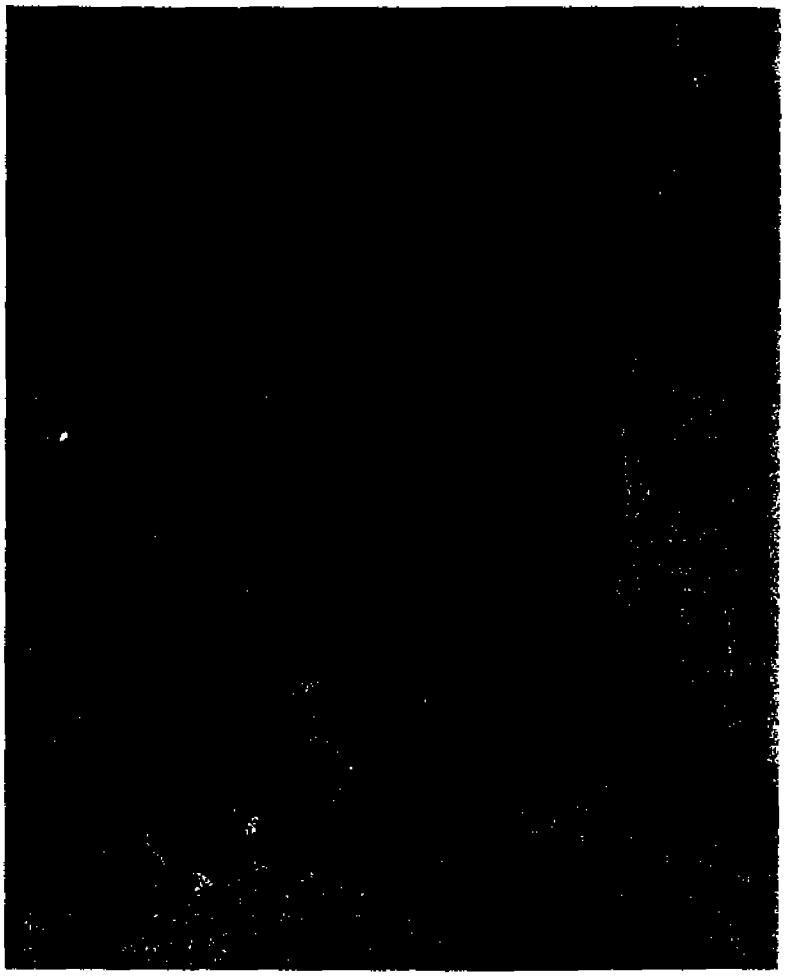


Figure 3-3. Amorphous gel (probably alumina) coating fine-grained goethite and gibbsite particles. X-ray data show gibbsite, goethite, and trace amounts of quartz. The total SiO_2 content of this soil is less than 5 percent.

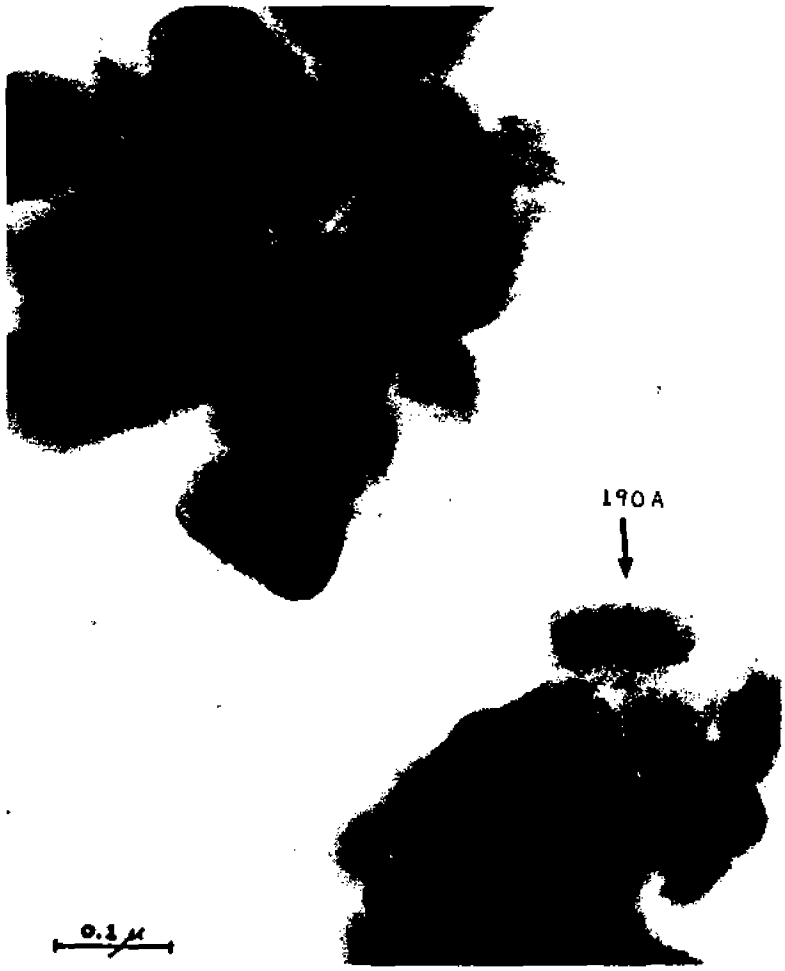


Figure 3-4. Amorphous silicic acid coatings on quartz grains. The quartz was pulverized, sonically dispersed in distilled water, and sprayed as a mist onto the electron microscope grid.

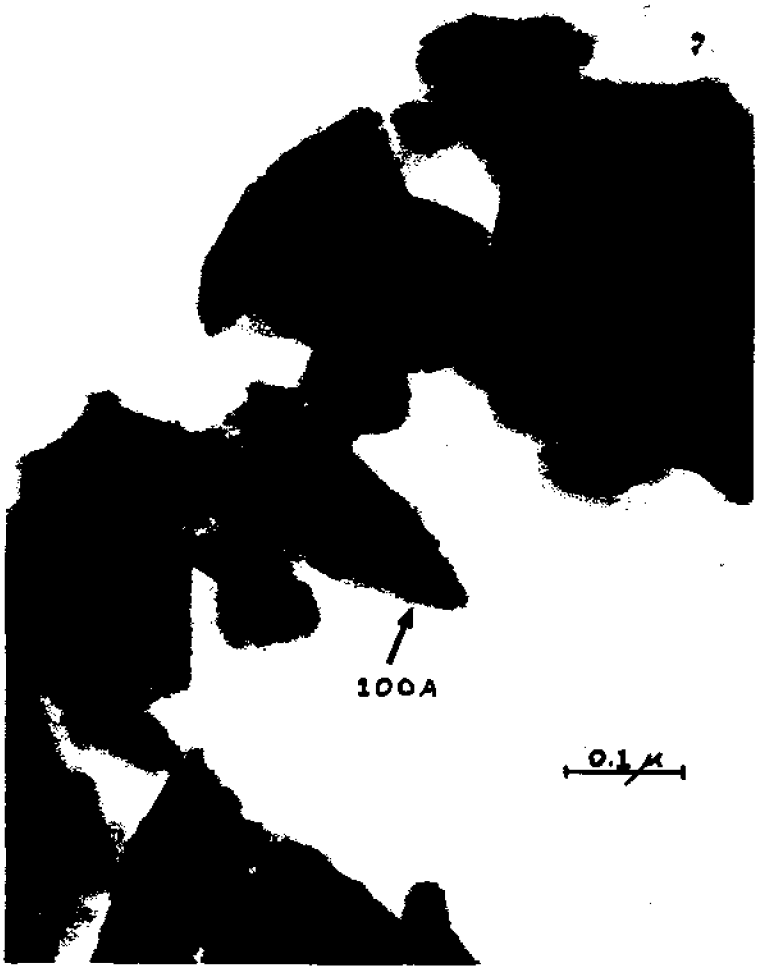


Figure 3-5. Amorphous gel-coatings on ablite crystal. This sample received the same treatment described in Figure 3-4.

Figure 3-6. Amorphous gel-coatings on obsidian (Apache Tears). This sample received the same treatment described in Figure 3-4.

Figure 3-7. Amorphous silicic acid precipitated from a water extract of Cheto-montmorillonite from Arizona.

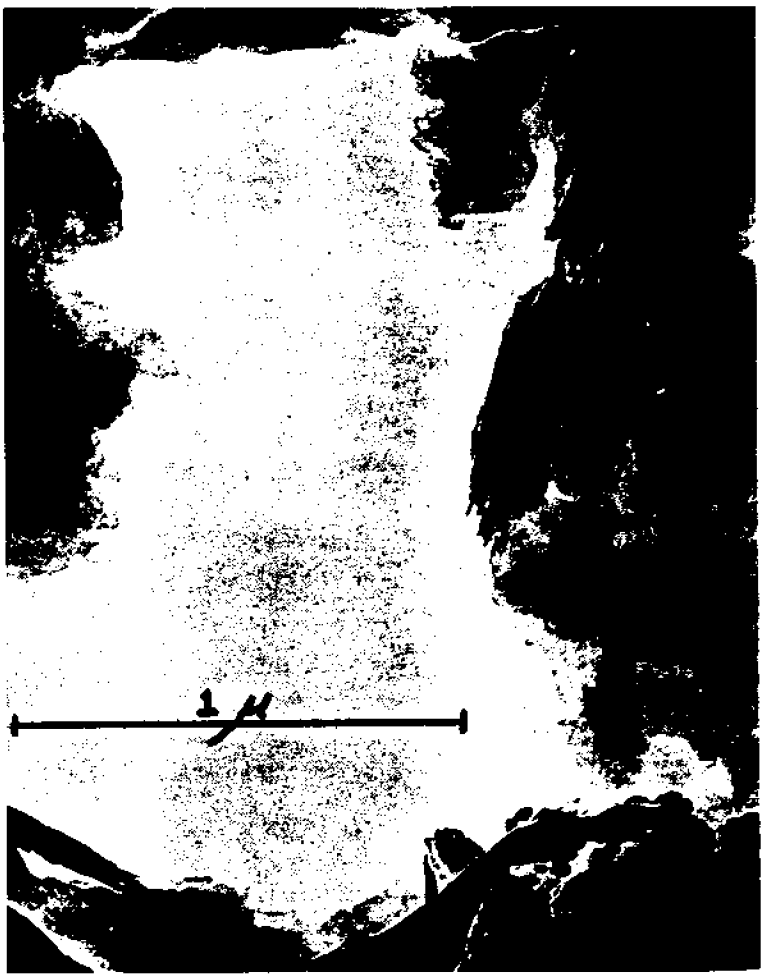


Figure 3-8. Amorphous silicic acid (arrow) associated with Cheto-montmorillonite.

The importance of amorphous mineraloids in soil takes on new significance when viewed in the light of these new data. The data of Jones et al. and data contained in this paper, show that the noncrystalline fraction of soils do not exist as particulate bodies, but as films on crystalline minerals. Such being the case, the surface chemistry of soils can be presumed to be strongly influenced by this coating when it exists.

Gel-like surface coatings can be clearly seen in Figure 3-1. The soil material shown in Figure 3-1 was previously treated with sodium dithionate to remove reducible free iron oxide. For this reason one can conclude that the surface coating is not ferruginous. The encapsuled particles are halloysite, and there is good reason to believe that the coating is a noncrystalline hydrated alumino-silicate. A particularly interesting feature of Figure 3-1 is the manner in which the gelatinous films hold the halloysite particles together.

Figure 3-2 illustrates a similar situation. In this case, kaolinite particles are held together through the cementing effects of the gel-like coating. This sample had received no chemical treatment. The particles were sonically dispersed and the suspended particles were sprayed on the electron microscope grid as a mist. The dense irregularly shaped particles are the free iron oxide. This sample contained approximately 15% free iron oxide by weight. It is now certain that iron oxide, even when amorphous to X-rays, may exist as discrete particles and may not act as cementing agents. The amorphous hydrated iron oxides are also coated with gel-like material.

Gel-like coatings have also been observed on soil particles consisting entirely of gibbsite, goethite, and some organic matter (Figure 3-3). In this case, the coating was presumed to be an aluminous gel since the total silica content was less than 5%, all of which could be allocated to quartz.

Similarly, gel-like coatings have been observed on quartz grains. This is shown in Figure 3-4. To prepare the specimen shown in Figure 3-4, a large quartz crystal was pulverized to clay-sized particles, sonically dispersed in water, and sprayed on grids. The surface film is in appearance very much like those in Figures 3-1 and 3-2. Albite (Figure 3-5) and obsidian (Figure 3-6) also give similar results when prepared in the same manner.

After examining many soil and geologic materials, it became apparent that surface coating is a common feature.

In arid regions where surface crusting is common, the cementing agent most probably is silica. Figure 3-7 illustrates silica bodies precipitated from a water extract of Cheto-montmorillonite from Arizona. The dissolved silica most likely occurs as monomeric silicic acid, but the precipitate appears as a tangled mass of strings of beads. This same precipitate can be seen on the surface of montmorillonite particles in Figure 3-8.

Role of water and texture in crust development

Before soil particles can be effectively cemented together, they must be brought into close proximity with their neighbors. If the particles are fine-grained, the system will possess a large specific surface area and, therefore, present a greater probability for making large numbers of contact per unit volume of the system. The numbers of contact will also depend on the size, shape, size distribution, and packing arrangement of particles. In any given material, packing is the only physical variable which is subject to change and manipulation. Water and the nature and concentration of electrolyte dissolved in it are particularly important to the final spatial arrangement of soil particles in the crusted state.

A saturated or near water-saturated state is an essential initial condition for crust formation. As water is removed by drainage and/or evaporation, pore water pressure increases negatively. If the surface layer consists of water-stable aggregates, water drains rapidly from the large inter-aggregate pores, and subsequent evaporation results in increased negative pore water pressure within the aggregate, which in turn brings particles in aggregates closer together. If, on the other hand, the surface layer consists of aggregates which slake in water, large pores disintegrate upon wetting and pore size distribution is narrowed and shifted to the fine range.

Rough estimates of the negative pressures which can develop for various ideal textures can be made if it is assumed that pore diameter is equal to particle diameter. For sands (particle size $> 50\mu$), a maximum negative pressure of 0.06 bar can be attained before desaturating. Negative pressure approaching 0.5 bar can be attained in a system consisting of 5 micron particles. For clay-sized particles less than 2 microns in size, negative pressures in excess of 1 bar can develop. Furthermore, a 10-fold decrease in diameter of spherical particles causes a 1000-fold increase in the number of particles contained in a unit soil volume, and results in a proportionate increase in number of potential contact points.

The combined effects of reduced pore size, and therefore higher attainable negative pore water pressures, and increased number of contact points contribute to enhancement of bond formation. Based on field experience, frequency of crusting is much reduced when particles exceed silt size.

In the clay fraction, the nature of adsorbed cations and the concentration and composition of electrolytes in the pore water affect particle packing and arrangement as well. Sodic soils are more susceptible to crusting because particles disperse readily and become compacted under the compressive effects of negative pore water pressure. Increasing the ionic strength of the soil solution compresses the diffuse layer, thus diminishing repulsive interparticle forces. When repulsive forces are finally exceeded by attractive forces,

clay flocculation commences, leaving a system which resists crusting. Removal of salts from saline soils without providing means to replace sodium with calcium on the exchange complex is a common cause of crusting.

Mechanical actions of water also influence spatial distribution of particles in crusts. Beating action of raindrops or turbulence in an irrigation furrow can cause heavier and larger particles to concentrate at a point just below the surface. Horizontal stratification is a common cause for peeling of crusts from the underlying soil.

Stresses imposed on the soil surface during drying, and the distribution of these stresses ultimately control the number and distribution of rupture planes in a crust. If the system is inhomogeneous and anisotropic, and water is evaporated rapidly so that stress gradients develop, failure planes will tend to develop at the point of steepest gradient. Inhomogeneities normal to the surface cause cracking, while those parallel to the surface cause peeling.

Hsu (1963) showed that in concrete, microcracks formed at interfaces between coarse aggregate and mortar. Using elastic stress analysis, he was able to demonstrate that tensile stresses concentrate at interfaces which occur between two materials differing widely in elasticity. This suggests that soil inhomogeneities which arise from uneven mechanical packing and chemical flocculation influence stress and stress distribution in a drying system, which in turn determine crust characteristics.

In laterites, each particle is held in place by a soft cement. If it is exposed and subjected to intense desiccation, irreversible hardening and crusting are the end results.

Cementing Agents

Cementing agents can be categorized in a number of ways. It would be useful, for example, to know to what extent a cement is soluble in water, whether the solid phase is in equilibrium with the dissolved phase, whether the cementing agent is crystalline or noncrystalline, whether the solid phase dries irreversibly or rehydrates and redissolves upon rewetting, whether the dissolved phase exists, as ions, ion-pairs, or undissociated molecules, whether the dissolved phase precipitates as discrete particles or as surface coatings on mineral surfaces, and whether the cement can acquire charge in the solid phase.

There are other features of cements which would be important. Consider the gelatinous coatings in Figure 3-1. Will the gelatinous material on two adjacent particles coalesce upon contact to form a continuous coating? A careful examination of Figure 3-1 suggests that such behavior is likely.

Amorphous cementing materials are solids with short range order, and as such are particularly effective cementing agents because of their ability to form curved solid-air interfaces, and thus make definite contact angles with other solids. Unlike crystalline solids, amorphous gels at some time during the initial stages of crust formation may flow, spread, or fuse. When the soil is water-saturated, gels are, and in fact, behave as viscous liquids, but upon dehydration become hard, elastic bodies. This capacity to change reversibly from a viscous newtonian liquid to an elastic hookian solid in a single drying cycle imparts to a crust most of its essential features.

In the irrigated lands of the arid and semi-arid regions, silica is the most likely cementing agent, whereas in the humid tropics, noncrystalline hydrated alumino-silicate and sesquioxides are the likely cause for induration and crusting. Irreversible crusting in laterites appears to be associated with the inability of sesquioxides gels to resorb water once it is dehydrated. Silica gel, on the other hand, as reported by Kruyt and van Klooster (1927, p. 218) can resorb water even when dried to the elastic state (6-8 moles water per mole of SiO_2).

Silica

If there is a universal cementing agent of the arid and semiarid regions, it is probably silica. Water-soluble silica in soils range from more than 300 ppm SiO_2 in strongly alkaline soils (Kelley and Brown, 1939) to less than 1 ppm (Fox et al., 1967) in latosolic soils. At ordinary temperatures, amorphous silica is soluble to the extent of about 120 ppm, but soil solutions rarely reach this value and generally range between 10-25 ppm. Gifford and Frugoli (1964) were able to measure, after repeated extractions, three stages of constant silica solubility. It is now generally believed that silica in natural waters exists as monomeric H_4SiO_4.

The fact that silica in soil solutions rarely approach the saturation value of 120 ppm was interpreted by McKeague and Cline (1963) to indicate its adsorption on soil surface. Hingston et al. (1968) measured maximum adsorption of silica on goethite surface and showed that highest maximum adsorption occurred at pH 9. Whatever the reason for the low concentration of silica in soil solutions relative to its saturation value, it is difficult to attribute interparticle bonding in crusts to dissolved silica. A liter of soil, for example, holding 500 ml of 50 ppm silica solution will contain 0.25 gm dissolved silica, hardly sufficient to account for crusting in medium and heavy textured soils. On the other hand, if one considers the alkali soluble silica determined by the method of Hashimoto and Jackson (1960), which amounts to several percent by weight, and if we further assume that this silica exists as coatings on particles, then the case for silica as a cementing agent can be reevaluated.

The nature of amorphous silica in soils is particularly important. When it occurs as opaline silica bodies as in phytoliths, it behaves like other rigid particles, but if it occurs as a viscous gel capable of flow and coalescence under the compressive stress of negative pore

water pressures, then it can become an effective interparticle cementing agent. The cement must ultimately transform from a viscous liquid to an elastic solid. Table 3-1 shows data which relate the property of silica gel to its degree of hydration. When silica is in the form of a gel, 30-40 moles of water is associated with each mole of silica. At the stage of drying wherein each mole of silica is associated with 6-8 moles of water, the material becomes elastic. Pure silica gel rehydrates, but displays some hysteresis. More important, once dried to the elastic state it does not return to the viscous state. This suggests that in crusting soils at least, rigid interparticle silica bridges are ruptured through swelling pressures, or that silica becomes viscous upon rehydration. The former may be true in acid soils whereas the latter may hold in alkaline soils.

Table 3-1. Property of silica gel as a function of water content (after Kruyt and Van Klooster, 1927).

Moles water per mole SiO_2	Property of
40-30	may be cut
20	fairly stiff
12	may be pulverized
8	somewhat elastic
6	apparently completely dry

Iler (1955) has compiled and plotted data which relate solubility of amorphous silica to temperature. Solubility of amorphous silica approaches zero values at 0° C, but increases linearly at the rate of about 4 ppm for every degree C increase in temperature. The day-night temperature difference in surface temperature of arid region soils could reach 20 to 25° C. A soil solution with 20 ppm SiO_2 at 20° could conceivably reach 4 to 5 times this concentration at midday. Silica solubility increases sharply above pH 8 or 9, but is independent of pH changes below these values. Garrels (1965) has analyzed a solution of pH 6 containing 6 ppm sodium and 20 ppm SiO_2, a composition not unlike those found in a water-saturated crusting soil. If such a solution were subjected to evaporation, silica would precipitate upon reaching a saturation value of 120 ppm, CO_2 would be lost to the atmosphere, sodium concentration would increase, and the pH would rise above 9. Although Garrels was referring to a solution isolated from weathering rock, this is probably a fair approximation of the type of reactions which occur in a rapidly evaporating surface soil. This suggests that the chemistry of soil solution as measured by conventional laboratory extracting procedures gives little indication of the solution compositions at the crucial stages of crust formation.

McKeague and Cline (1963) state that in soil solutions other than those of alkali soils, dissolved silica exists mainly as monomeric H_4SiO_4. Soluble silicates is another possibility, especially in soils of the arid and semi-arid regions. Soluble silica precipitates in the presence of salts and this precipitate redissolves upon dilution if the salt is of a monovalent metal, but is insoluble if precipitated by a salt of a polyvalent metal (Iler, 1955).

Kelly and Brown (1939) measured 375 ppm SiO_2 in a soil extract of pH 10.4. Chloride, sulfate, and carbonate anions were also measured in high concentration along with potassium and sodium ions, but divalent calcium and magnesium were measured in negligible amounts. Most solutions of soluble silicates contain mixtures of polysilicate ions (Iler, 1955), so that upon increasing salt concentration through evaporation the resulting precipitate is a relatively insoluble amorphous mass.

There is considerable literature on the properties of pure silica gels (Iler, 1955) and soluble silicates (Vail, 1952). Silicates with SiO_2/NaO_2 mole ratio of 0.48:1 to 3.9:1 are reported by Iler (1955). The molecular weights of dissolved silica increased from 60 to 400 over this range and attained values as high as 2000 in a potassium silicate with a SiO_2/K_2O ratio of 3.8:1. Although it is probably true that silica exists as monomeric H_4SiO_4 in river water, extension of this argument to soils, especially to soils of the arid regions, is not justified.

Figure 3-7 shows that when a silica-bearing solution is isolated from montmorillonite and dried, dissolved silica precipitates as spherical bodies. The spherical bodies coalesce upon contact, and in two dimensions appear as a string or network of intersecting circles. Carmen (1940) suggested that condensation of monomeric $Si(OH)_4$ within and between these silica bodies leads to rigid, highly porous bodies consisting of a tangled network of branching chains. This body can cement other soil particles together in two possible ways.

In the first case, silanol groups can form hydrogen bonds with oxygen sheets on clay, siloxane (Si-O-Si) linkages with quartz or other silica minerals which are known to be covered with silanol groups. In these, direct bonding between silica and soil particle is assured.

One can also visualize a second case in which silica forms a continuous film in which all soil particles are embedded. This is similar to the coat-of-paint effect described by Greenland (1965). A combined effect of direct bonding of cement and particle, and coat-of-paint effect could result in considerable crust strength.

Although siloxane linkages form permanently, gels may be repeptized by alkali (Carmen, 1940). This, along with shearing stresses imposed by swelling, may account for gradual softening of crusts upon rewetting.

Evidence of the kind presented in Figures 3-4, 3-5, 3-6, 3-7, and 3-8 which show that many particles are coated with silicious, gel-like coatings, strengthens the thesis that silica is the major cementing agent in crusting soils of the arid regions. The key to management of crusting soils may lie with manipulation of variables which controls silicious gel-coatings on mineral surfaces.

Amorphous sesquioxides and alumino silicates

Unlike silica, the oxides and hydrous oxides of iron and aluminum are extremely insoluble in the pH range

normally encountered in soils. In soils containing less than 5% free oxide, one can generally show a positive correlation between aggregate stability and free iron oxide content (Kemper and Koch, 1966), but in some latosols with high aggregate stability no such relationship exists (Cagnuan and Uehara, 1965). Deshpande et al. (1964) showed, however, that removal of alumina with acid resulted in loss of stability. Greenland et al. (1968) furthermore showed that iron oxides exist as discrete particles and not as coatings on clay surfaces. Jones (1970) has shown that this is true in soils containing 15-25% amorphous to poorly crystalline iron oxide.

There is no published evidence for the existence of amorphous alumina in soils although some have speculated on its existence. More commonly, alumina exists as gibbsite, boehmite, or diaspore, with the latter two rarely occurring in soils. However, minute quantities of alumina impurities can severely alter clay-water interactions in aqueous suspension of Wyoming bentonite (Davey and Low, 1968).

In a soil containing less than 5% total SiO_2, gel-coatings on gibbsite and goethite particles were noted. The soil was a Gibbsihumox from Hawaii. This is probably the first direct evidence for the existence of amorphous aluminum hydroxide in soils (see Figure 3-3).

The effectiveness of sesquioxides as interparticle bonding agents probably arises from their surface charge. Surface charge of oxides depends on the concentration of potential determining ions in solution. In oxide systems, the potential determining ions are H^+ and OH^-. Adsorption of protons render the surface more positive and adsorption of hydroxyls more negative. At the isoelectric point or zero point of charge, the net surface charge is zero.

Soils are rarely monomineralic and generally contain minerals with constant charge surfaces, such as montomorillonite or vermiculite, as well as a small quantity of mineral or mineraloids of the constant potential (variable charge) type. It is easy to visualize bonding between a negatively charged particle and a positively charged sesquioxide or aluminosilicate.

A paper by Parks and DeBruyn (1962) which describes a method for determining the zero point of charge on hematite is particularly helpful in explaining the chemistry of oxide surfaces. Atkinson et al. (1967) have conducted a similar analysis for goethite, and Yopps and Furestenau (1964) have measured the zero point of charge for corundum ($A1_2O_3$). The zero points of charge for hematite, goethite, and corundum reported by the above workers were, respectively, at pH 8.5, 7.8 and 9.1. At pH values above the zero point of charge, oxides possess net negative charge, and positive charge below it. Hingston et al. (1967), however, have shown that adsorption of certain anions by these surfaces shifts the zero point of charge to lower pH values. Mekaru and Uehara (1972) have measured an increase in cation exchange capacity of 25 me/100 gm to 216 me/100 g in a ferruginous soil by adding phosphate to the soil.

All anions do not, however, have the same effect on surface charge. Chlorides and nitrates are adsorbed as counter ions and remain in the diffuse layer, whereas phosphate, oxalate, citrate, etc. actually displace hydroxyls coordinated to the metal ion in the oxide lattice. Anions which are retained as counter ions are called nonspecifically adsorbed anions, whereas those that enter into coordination with metal ions are referred to as specifically adsorbed anions (Hingston et al., 1968). This type of adsorption has an inhibiting influence on oxide crystalization (Schwertmann et al., 1968).

Phosphate is probably an effective dispersing agent because it neutralizes positive charge and furthermore raises that net negative charge on oxides and noncrystalline alumino silicates. Schofield and Samson (1954) have shown that kaolinite can be effectively deflocculated by addition of small amounts of sodium oxalate. Neutralization of positive charge by oxalates and deprotonation of the surface by addition of NaOH was essential for deflocculation.

The oxides and hydrous oxides of iron and aluminum possess a hydroxolated surface. Below the isoelectric point or zero point of charge, protons are adsorbed and the hydroxyls are protonated in aquo (Fe, $A1\text{-}OH_2^+$) groups. Above the zero point of charge, the hydroxyl is stripped of its proton, leaving net negatively charged surfaces containing (Fe, $A1\text{-}O^-$) groups. Bonding between net negatively charged and positively charged surfaces as a first hypothesis appears to be most reasonable. Aguilera and Jackson (1953) measured a higher cation exchange capacity in a deferrated soil and suggested that the cause was neutralization of negative site by oxides. Greenland et al. (1968), on the other hand, present electron micrograph evidence which suggests that iron oxide particles behave very much like negatively charged gold and silver iodide particles. The evidence to date suggests that iron oxides do not act as cementing agents in soils until they form a continuous matrix, and do not act as cements when they occur as discrete bodies as reported by Greenland et al. (1968), and Jones (1970). The distinction between a laterite and a latosol may very well be determined by this difference in the nature of the oxides.

The suggestion of Deshpande et al. (1964) and Greenland et al. (1968) that aluminum oxide is responsible for anion adsorption and net surface charge raises the question regarding the nature of soil aluminum. The results of Jones et al. (1969, 1973) and data contained in this paper suggest that amorphous aluminum silicates and alumina coat soil particles. If aluminum is four-coordinated as in zeolites, the resulting alumino silicate possess high net negative charge. On the other hand, if aluminum is six-coordinated as in kaolinite or gibbsite, the mineraloid surface will be of the variable charge type. It is highly unlikely that four-coordinated aluminum could exist for very long in soils

of the type examined by Jones et al. The high resolution obtained by these workers reveals that, unlike iron oxide, amorphous aluminum silicate forms a continuous coating around all particles.

Quite clearly, amorphous sesquioxides and alumino-silicate act in the coat-of-paint manner. Although these coated particles can be sonically dispersed, they immediately reflocculate upon removal of sonic energy, indicating that there is a net attractive force between particles. Dissolution of the coating by boiling in alkali (Na_2CO_3 or NaOH) causes dispersion.

The hardness and permanence of laterite crust is probably due to the oxides and hydrous oxides of iron and aluminum occurring as a continuous matrix. This feature of sesquioxides had led some to believe that free iron oxide is an important cementing agent in all soils. The best evidence now suggests that effective interparticle bonding occurs when a cementing agent forms a continuous matrix throughout the system. Bonding occurs not so much between cement and particle as between cement-coated particles.

Organic Matter

The published work on organic matter-clay interaction is extensive. Fortunately, a number of review papers on the topic are available, of which the reader may find those by Greenland (1965a, 1965b) brief and to the point. Greenland (1965a) has included two pertinent tables—one on forces involved between clays and organic compounds, and another on properties of clay systems which influence adsorption of organic compounds. He has divided forces into coulombic and Van der Waals, and the latter further separated into polar and nonpolar bonds. Surface properties which influence adsorption were given as extent, accessibility, chemical nature, surface charge, exchangeable ions, and configuration of surface. The properties of organic compounds were listed as charge, size polarity, polarizability, and flexibility.

There appears to be an inherent contradiction in discussions on bonding mechanism in soils, for one is apt to find the same arguments applied to crusting and aggregation. It turns out, however, that the contradiction is only apparent.

Aggregation is a process by which primary particles are bound together into compound units of varying size. Crusting is a form of aggregation. Aggregate stability is the index which is often used to distingusih crusting from noncrusting soil. It is a measure of the resistance of aggregates to slake in water.

The differences in mechanical strength of soil aggregates in the water-saturated and dried states separate crusting from noncrusting soils of the arid region. The regional qualification is necessary to exclude laterite crusts of the humid tropics, which are not substantially weakened by wetting. Crusts of the arid regions, on the other hand, lose their strength upon addition of water as a result of swelling, softening of cementing agents, or both.

The value of adding organic matter is not to increase the mechanical strength of a crust, but to render it stable even under water-saturated conditions. The work of Telfair et al. (1957) serves to illustrate this point. They puddled samples from a silt loam soil to which 5% by weight of finely ground alfalfa meal was added. The puddled samples were placed in cylinders and dried. After two years of burial, the exhumed cores were hard, low in permeability to water and air, and resisted slaking in water. Control cores without the added organic matter disintegrated quickly in water.

In parts of the world where paddy culture is common, large quantities of organic matter are often incorporated into the soil and thoroughly mixed with the puddled soil. When such a soil is allowed to dry, a thick, had crust forms which is difficult to till. Briones (1963) has shown that quite often the pulverized units of such a crust are extremely water stable. A similar process occurring in the intestinal tract of earthworms probably accounts for the high stability of earthworm casts.

The above examples point to the fact that organic matter is often a necessary but not sufficient agent for crust prevention. The initial state of the soil-organic matter mixture prior to drying has a decided influence on the suface soil condition after drying. It is for this reason that the modulus of rupture as an index of crusting hazard can give erratic and often misleading results. A sample with a high modulus of rupture but which resists disintegration in water would be less susceptible to crusting than a sample with an identical modulus of rupture value but which readily slakes in water.

Although the beneficial effects of organic matter are widely accepted, there is less agreement on the manner in which it improves soil structure. To summarize the published reports, the role of organic substance in stabilizing soil structure can be separated into two parts. On one hand, organic substance can reduce interaction of water with the inorganic colloids, and on the other, physically or chemically bind soil particles together.

In the first case, organic cations which are less hydrated than inorganic cations reduce the amount of water associated with the clay surface. Nonionic organic substance sorbed on clay surfaces can also function in this way and furthermore increase the solid-water contact angle when the surface is wetted. Kijne and Taylor (1967), for example, have shown that the heats of wetting of organo-montmorillonite complexes are much lower than their noncomplexed counterpart. In short, the damaging effect of water resorption is diminished in the presence of organic substances.

Soil structure can also be rendered more stable by the binding action of organic matter. This may involve physical entanglement of soil particles in a network of microbial mucilages. In other cases, polyvalent cations may link cation exchange site to polymer carboxyls. A more detailed account of bonding mechanisms can be

found in the review articles by Greenland (1965a, 1965b), Harris et al. (1966), and Martin et al. (1955).

Lewin and Reiman (1969) in a review paper on the subject of silicon in plant tissue cite references which show that silicic acids readily complex with simple organic molecules such as polyhydric alcohols and acids, as well as with more complex molecules such as methemoglobin, albumin, collogen, gelatin, insulin, nylon, pepsin, and laminarin.

Silicic acid coatings on mineral surfaces shown in Figures 3-4, 3-5, 3-6, and 3-7 should act as adsorption sites for organic matter. The specific adsorption of anions by iron and aluminum oxides has also been mentioned. It appears, then, that organic matter interacts with other cementing agents and possibly prevents crust formation by reducing the cementing action of silicic acid or sesquioxide rather than by contributing to more interparticle bonds.

Gypsum and lime

While gypsum and lime (calcite) occur in cemented polycrystalline forms as petrogypsic and petrocalcic horizons in soils, they probably do not act as cementing agents when added as amendments to crusting soils. The replacement of monovalent sodium ions with divalent calcium ions can account for most of the beneficial effect of gypsum and lime applications. Warkentin, et al. (1957) showed that while experimental swelling pressure measurements with Na-montmorillonite followed patterns predicted by theory, no good agreement was achieved with Ca-montmorillonite. The measured swelling pressure after initial compression was lower than theoretical values. The explanation of the deviation of Ca-montmorillonite from predicted behavior may rest with adsorbed silica on montmorillonite.

It is generally assumed in laboratory work with montmorillonite that the sample is pure and monomineralic. The sample used by Warkentin, Bolt, and Miller (1957) was bentonite (montmorillonite from Wyoming). In a differential dissolution study of montmorillonite from Upton, Wyoming, Hashimoto and Jackson (1960) measured 6.93% SiO_2 and 0.29% Al_2O_3 after boiling the sample in 0.5 N NaOH for 2.5 minutes. Their work also contains data which suggest that montmorillonite helps induce silica precipitation. Figure 3-7 shows amorphous silica extracted from Cheto-montmorillonite, and Figure 3-8 shows silica associated with the montmorillonite surface.

One alternative way to explain the experimental result obtained by Warkentin, et al. (1957) with Ca-montmorillonite is to treat it as a Ca-silica-montmorillonite system. In this system, the surface charge density consists of a constant part attributable to montmorillonite and a pH-dependent part associated with silica. The essential and crucial difference between the sodium and calcium system is the nature of cation adsorption on silica.

NaCl is an indifferent electrolyte, i.e., Na^+ is not specifically adsorbed on the surface of silica. On the other hand, $CaCl_2$ is not an indifferent electrolyte; Ca^{++} is specifically adsorbed on silica (Tardos and Lyklema, 1969; Lyklema, 1968).

In silica (constant surface potential), the surface charge density varies not only with pH, but also with electrolyte concentration. In addition, when ions are specifically adsorbed, the effective charge (total charge minus the charge in the Stern or compact layer) density is lowered. Swelling and particle dispersion is reduced, and problems with crusting are diminished.

This line or reasoning suggests that gypsum would be a more effective soil amendment than lime. Gypsum is a source of calcium but does not raise pH and surface charge density. Lime has the disadvantage of increasing pH in soils where increasing pH serves no useful purpose.

Bonding Mechanisms for Soil Crusts:

PART II.

Strength of Silica Cementation

Richard O. Gifford and Dianna F. Thran

Geologists and soil scientists have long recognized the cementing properties of silica in soil and rock formations. Silica is a major cementing agent in duripans, a hard layer found in certain arid region soils. Silica is also a cementing agent in the formation of surface crusts which occur on many soils following a cycle of wetting and drying.

This section reports the results of some specific experiments which were undertaken to explore the potential strength of silica as a cementing agent in soil crusts. Because natural soil particles have irregular physical dimensions and varying chemical compositions, glass spheres were used to simplify the system for experimental study. Most of the mineral material in

soils is crystalline silicates, and particle surfaces are often covered by a coating of amorphous material, especially in the less weathered soils of arid regions where amorphous minerals are common. Hence, the surface of a glass sphere may not be significantly different from many soil mineral surfaces, except in its geometry.

Glass beads (3M Superbrite) were washed in 0.1 N HC1 followed by 0.01 N HCl to remove surface alkali, rinsed free of chloride in distilled water, rinsed in acetone, and air dried. When a drop of distilled water was placed around a group of these beads, the spheres were rolled together by surface tension as the drop of water evaporated. Water evaporated last from the points of contact between the spheres. Any material dissolved in the drop of water was concentrated at the point of contact. Sufficient material was dissolved from the glass to cause beads of 500 microns diameter or less to be cemented together. The strength of the cement was sufficient to allow a pair of beads to be moved around together on a slide under a microscope. The cementing material appeared to be a volume of revolution about a line through the center of the spheres at the point of their contact. The diameter of the cementing deposit was about 1/10 of the diameter of the beads.

The strength of the cementing material between two spherical surfaces was determined with thin rods drawn from soft glass. Beads were formed on the ends of these rods by rotation in a flame. Pairs of beads of the same diameter were selected for use and washed with HC1, rinsed with silica-free distilled water, and dried with lens paper. The glass beads with rods were placed in a modified Cenco-DuNouy Interfacial Tensiometer. The rod of one bead was sealed inside one end of a short piece of plastic tubing and the plastic tubing was slipped onto the coupling of the moving arm of the tensiometer in place of the usual platinum ring. The rod of the matching bead was cemented into a small square of ¼-inch thick acrylic plastic. This bead was centered under the first bead by using stopcock grease to hold the plastic base in position on the tensiometer table which normally holds the container of liquid. The table was raised so the beads were placed in contact without force being exerted on each other. A drop of silica-free distilled water was placed around the two beads and a heating coil of nichrome wire wrapped around a glass sleeve was lowered around the beads. Current from a battery was applied to hasten drying. When all the water evaporated from around the beads, tension was applied to the bead pair by rotating the torsion wire of the tensiometer. A synchronous electric motor was used to provide a constant and reproducible rate of force application. When the cement between the beads broke, the motor was stopped and the force calculated from the tensiometer dial reading.

It was assumed that the area of the cementing bridge which failed was the cross sectional area of a cylinder whose diameter was the apparent size of the connecting material between the beads. The tensile strength was calculated from the measured force and apparent area. The median strength found in 9 tests with soft glass beads was 1.5 bars. The median strength found with 9 pairs of beads made from fused silica (99.8% SiO_2) was 1.8 bars.

It appeared that small bridges between the beads were stronger than large ones. In attempting to find an explanation for this phenomenon, we discovered that the cementing material was not a solid cylinder between the beads, but an irregular hollow cylinder or spiral. The deposits were examined and photographed at 100-power magnification viewing along the axis of the support rod. The areas of the deposits were calculated by planimetering the areas of projected negatives of the deposits. The area of the deposit measured with the planimeter was less than the apparent area calculated from the diameter of the bridge. The deposits were 33% to 78% solid (mean, 45% solid).

Detailed observation of the last stages of drying, using a variety of bead sizes, cementing materials and lighting, showed the following steps during the formation of the cementing deposit. As the volume of the water drop decreases, a volume of minimum surface area forms between the beads. At a point in the drying, the liquid between the beads changes from clear to cloudy; this occurs at or near the final diameter of the cementing bridge. Continued drying apparently takes place on the surface of the cylinder of gel. The wall of the cylinder eventually ruptures due to decreased internal pressure brought about by the evaporation of water. A hollow cylinder is formed with a break in the wall at one or more points. In other cases, uneven heating during evaporation causes the material to gel at one point and then progress in a spiral around the point of contact. These patterns of cementing material are shown in Figure 3-9.

Figure 3-9. Photographs showing the spontaneous cementing patterns formed between glass beads upon drying.

The cementing material was not chemically analyzed. Although it is possible that small amounts of other materials were dissolved from the acid-washed glass, the major constituent was undoubtedly silica. The cemented bridges between beads formed from fused silica were slightly smaller, but had the same patterns and strength as those of soft glass beads. Glass beads were cemented together by solutions containing silica, as well as by silica dissolved from the beads. A stock solution of silicic acid was prepared by passing a sodium silicate solution through a hydrogen-saturated ion exchange column (Dowex 50W-X8). The stock solution was diluted to prepare solutions of 10 to 100 ppm silica. Silica content was determined colorimetrically. Silica-free distilled water from a metal still stored in plastic containers was used throughout the experiments.

The results from a number of tests are summarized in Table 3-2. Not all attempts were successful. Vibration within the laboratory building caused a sizeable percentage of the bead pairs to be broken apart before they were completely dry. Undoubtedly some of the low values included in the data are the result of vibration-induced stress within the cement. The occasional high values which make the mean greater than the median may represent more nearly the strength of the material actually cementing the beads together. Deposits of silica formed in more nearly vibration-free conditions or with very slow drying might have strengths in excess of the maximum reported here. There remained a tendency for the smaller diameter bridges to be stronger than the larger ones, even when the area of the bridge, not simply its diameter, was taken into account by planimetering the area (Figure 3-9). The smaller diameter bridges were also shorter from bead to bead, so the possibility of flaws in the bridge was less.

Table 3-2. Tensile strength of silica-cementing glass beads.

Silica solution concentration	Number of trials	Tensile strength		
		Mean	Median	Maximum
ppm		bars	bars	bars
10	59	3.2	2.6	8.3
100	19	3.4	2.5	7.4

All of the data are the result of single wetting and drying cycles. Tests with repeated wetting and drying cycles showed a tendency for greater total force to separate the two surfaces, but the force per unit of contact area did not increase. Rinsing the glass spheres in 0.1% HF before use did not change their cementing characteristics. The bridge formed between the beads is readily soluble in 0.01% HF. A drop of water added to a pair of cemented beads on the bridge usually caused the bridge to break, but did not dissolve it.

Although the strength of the cementing material between these spherical surfaces is significant, it probably can explain only a part of the strength of natural soil crusts. The strength of soil crusts are of the same order of magnitude as the strengths we report for silica cement between beads, however, only a fraction of the gross area of a soil crust test specimen contributes to its strength. A more detailed description of the role of silica cementation as an agent in the formation of hard soil crusts will require more information on the geometry of soil particle arrangements in crusts.

• CHAPTER 4

Crust Strength and Cracking:

PART I.

Strength

W. Doral Kemper, Daniel D. Evans, and Hugh W. Hough

In general, the strength of soil crusts depends on the strength of the particle-to-particle bonds. Consequently, much of the discussion by Uehara and Jones in the previous chapter is directly relevant to strength of crusts. In fact, strength of soil crusts may be written as: Crust Strength = f (bond strength, number of bonds, particle shape) [4-1]

The effect of soil components and wetting and cultivation history on crust strength, as discussed below, is primarily through their effects on these three parameters.

Effects of Soil Components on Crust Strength

As a contribution to the W-66 project, Hough (unpublished data, H. H. Hough) created synthetic soils from a clay sized hydrous mica, a silt size fraction from degraded Niobrara shale, and quartz sand (90% fine, 10% medium) of the textures indicated on the texture triangle of Figure 4-1. He used the procedure recommended by Richards (1953) to determine the modulus of rupture for each of the mixtures. This involves placing the material in a small frame, wetting it, allowing it to dry at 60° C and testing the breaking strength. These measured moduli of rupture are shown as the numbers on the right of the solid circle representing each mixture in the texture triangle of Figure 4-1. It is apparent that modulus of rupture generally increased as the mixtures contained more clay. In these mixtures, modulus of rupture was correlated with the hydrous mica clay content by a coefficient of 0.95. The moduli of rupture of these mixtures were generally higher than those for the natural soils studied by Hough. He found that in soils which were not highly sodic, the moduli of rupture ranged from 0 to 0.5 bar, which is the general range of productive agricultural soils which have no special crusting problems.

The mixtures used by Hough had little if any structure to begin with. Consequently, when they were wet and subsequently dried, there were few, if any, forces resisting the surface tension forces bringing the components into the most intimate contacts where the number of particle-to-particle contacts was maximized. The high moduli of rupture found by Hough for his samples with high clay content represent the magnitude of the modulus of rupture values which may be obtained when initial structure is minimized.

Clay does play a positive role in stabilizing natural soil aggregates against disintegration during wetting (Kemper and Koch, 1966). Moduli of rupture and crusting strength are often highest in natural soils which have a high silt and fine sand content and are structurally unstable when wet (Kemper et al., in press). When soils are highly sodic, the osmotic swelling forces pull water into the diffuse layer of adsorbed sodic ions, pushing clay particles apart from each other, breaking particle-to-particle bonds which maintain aggregate structure, and negating the wet phase bonding effect of clays. Consequently, sodic clays are pulled into closely oriented, and often laminated configurations by surface tension forces during drying. Under these highly sodic conditions, the modulus of rupture will often be a maximum in soils with high clay contents. In general, wet aggregate stability of western U. S. soils approaches zero and modulus of rupture approaches a maximum for the texture involved when the exchangeable sodium percentage of a soil goes over 20% (Brooks et al., 1956). Soils with exchangeable sodium contents of less than 10% can generally produce good crops under careful management.

Hough also studied moduli of rupture on mixtures where a montmorillonite clay from Greybull, Wyoming was used instead of the hydrous mica clay. While there was an overall increase in the modulus of rupture as the clay contents of his mixtures increased, there was much more variation from sample to sample. More

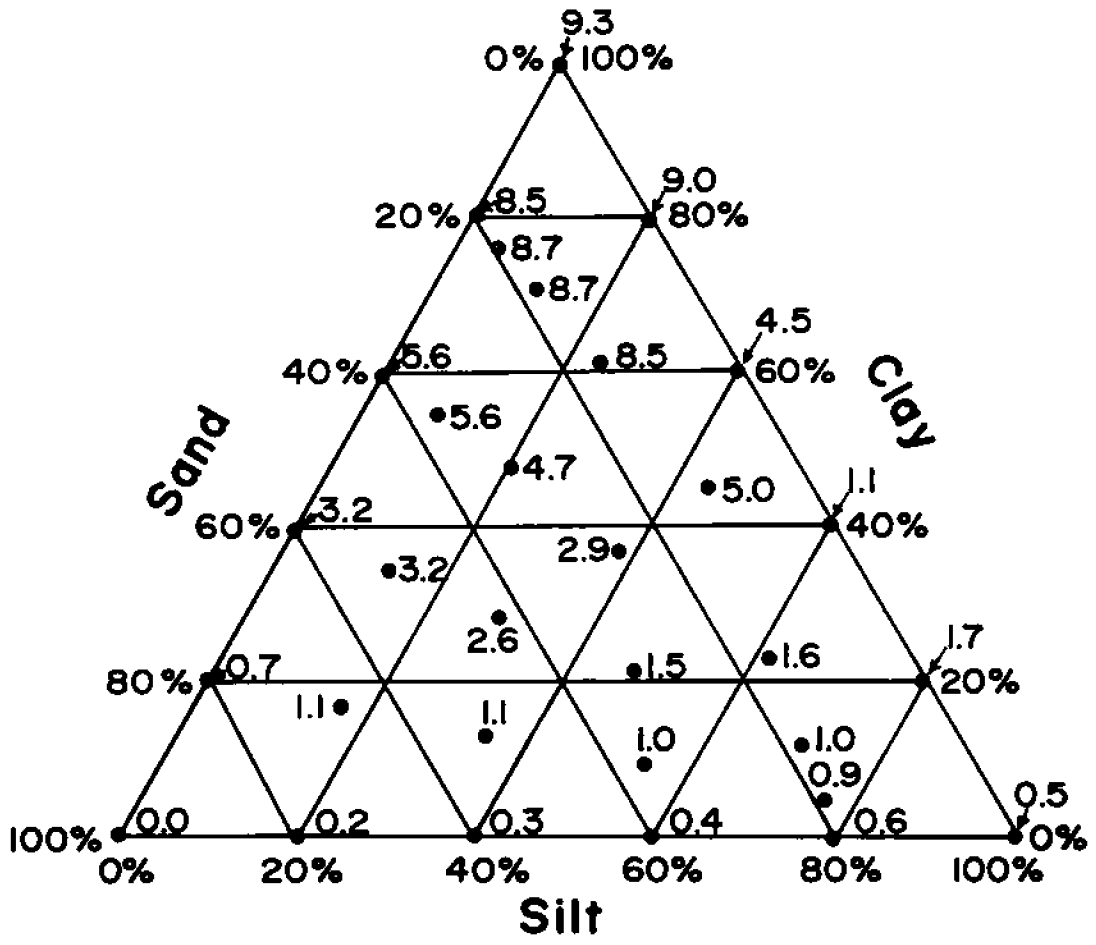


Figure 4-1. Textural triangle showing 31 mixtures used for measurements of soil crusting strength. (Number to right of each point is modulus of rupture in bars.)

blocks warped and cracked during drying. Apparently the greater surface area and higher swelling and shrinkage characteristics of the montmorillonite clay places more stresses on the crust during the drying process, when these clays are mixed with other non-swelling components, and cause more planes of weakness and fracture than when hydrous mica clays are dominant.

Plant residues (leaves, straw, roots, etc.) lose their physical strength as they are decomposed. Therefore the plane in which they were incorporated in the soil generally becomes a plane of weakness. Consequently, incorporation of organic materials generally decreases crust strength when the organic matter has time to decompose.

Fresh decomposing organic matter increases the stability of soil aggregates when they are wetted (Miller and Kemper, 1962). This increased stability is associated with binding of particles together by fungal mycelia on a macro scale, binding of closely adjacent surfaces by organic molecules, and changes in the hydration characteristics of the soil so that wetting does not cause as much disruption of the aggregates. The remains of the residues provide planes of weakness and fracture which relieve swelling stresses and reduce internal fracture of the aggregates along other planes in much the same manner as scoring concrete slabs in regular squares reduces fracture within those squares as they contract and expand. These stabilizing effects of freshly added organic matter on aggregate stability reduce the degree to which freshly cultivated soil disintegrates into a dense structureless mass when wet by water. The resulting large voids and reduced opportunities for particle-to-particle bonds result in a material with a much lower modulus of rupture when it dries.

When seedlings have adequate aeration, they can generally emerge through a moist soil surface. Crusts develop strength as their water evaporates. Surface tension forces draw particle surfaces into intimate contact (where H bonding, Van der Waals forces and other short range forces bond these particles together) and slightly soluble materials such as silicates, hydroxides, etc. are forced to particle-to-particle contacts by

receding menisci and precipitated as semicrystalline cementing agents as drying takes place. At the same time, the matrix generally shrinks to some extent (except for sandy soils) and cracks develop at planes where the strength is least. Since water content is a prime determinant of crust strength, the crust will generally crack along a plane of highest water content if differential drying takes place.

Quantitative measures of crust strength as a function of water content were obtained by Hanks and Thorp (1957), and Bennett et al. (1964). In general, their findings indicate that crust strength increases by a factor of about 3 as water content of the surface layer decreases from field capacity to the wilting point. A reasonably linear relation (negative slope) between water content of the soil and crust strength was noted by Bennett et al. for water contents from air dryness to considerably above the field capacity. Relations between modulus of rupture and water content obtained for two soils by Kemper, Olsen and Hodgdon are shown in Figure 4-2.

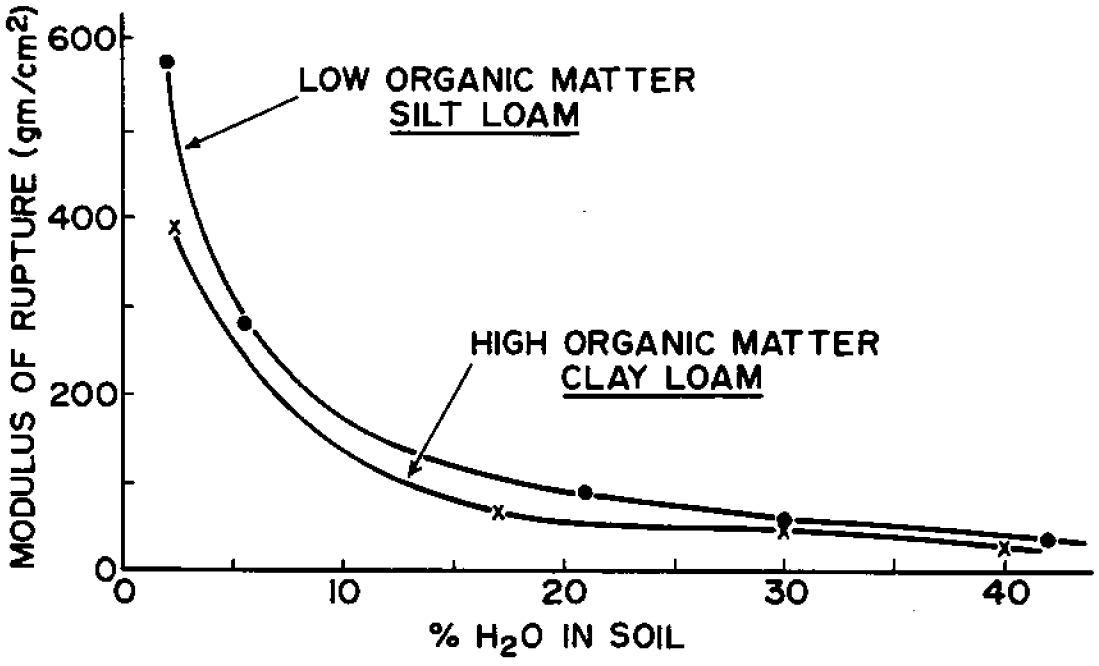
Effect of Wetting History and Cultivation on Crust Strength

The energy involved as raindrops strike the soil surface, and the subsequent disintegration of the top few mm of the soil, have been discussed in detail (Moldenhauer and Long, 1964, 1970). This disintegration of the original soil structure tends to leave the surface few mm in a monograin state. Subsequently, as drying takes place, surface tension forces pull the components of this layer together, forming a dense, strong crust. The rain-formed crusts will be thicker when the raindrops are larger because these larger drops have more energy and "blast" deeper holes, destroying the original structure to a greater depth. In general, however, rain-formed crusts are less than 5 mm thick.

Roughness of the original surface often has a strong effect on the strength of a rain-formed crust. If the surface is composed of large clods, the material dislodged from their surfaces by raindrop impact is largely eroded into the interclod areas. If the rain stops before the surface has been beaten flat, tops of clods will be covered by less of the disintegrated soil material and consequently thinner and weaker crusts occur on these tops and other high spots.

If the rainfall exceeds the intake rate and water ponds on the surface of the soil, soil particles blasted into suspension by raindrop impact tend to segregate, since the larger sand size materials settle out sooner and the finer clays are left on the top. This top high clay layer tends to shrink more than lower layers on drying, and as the crust cracks, the edges of intact crust segments tend to curl upward.

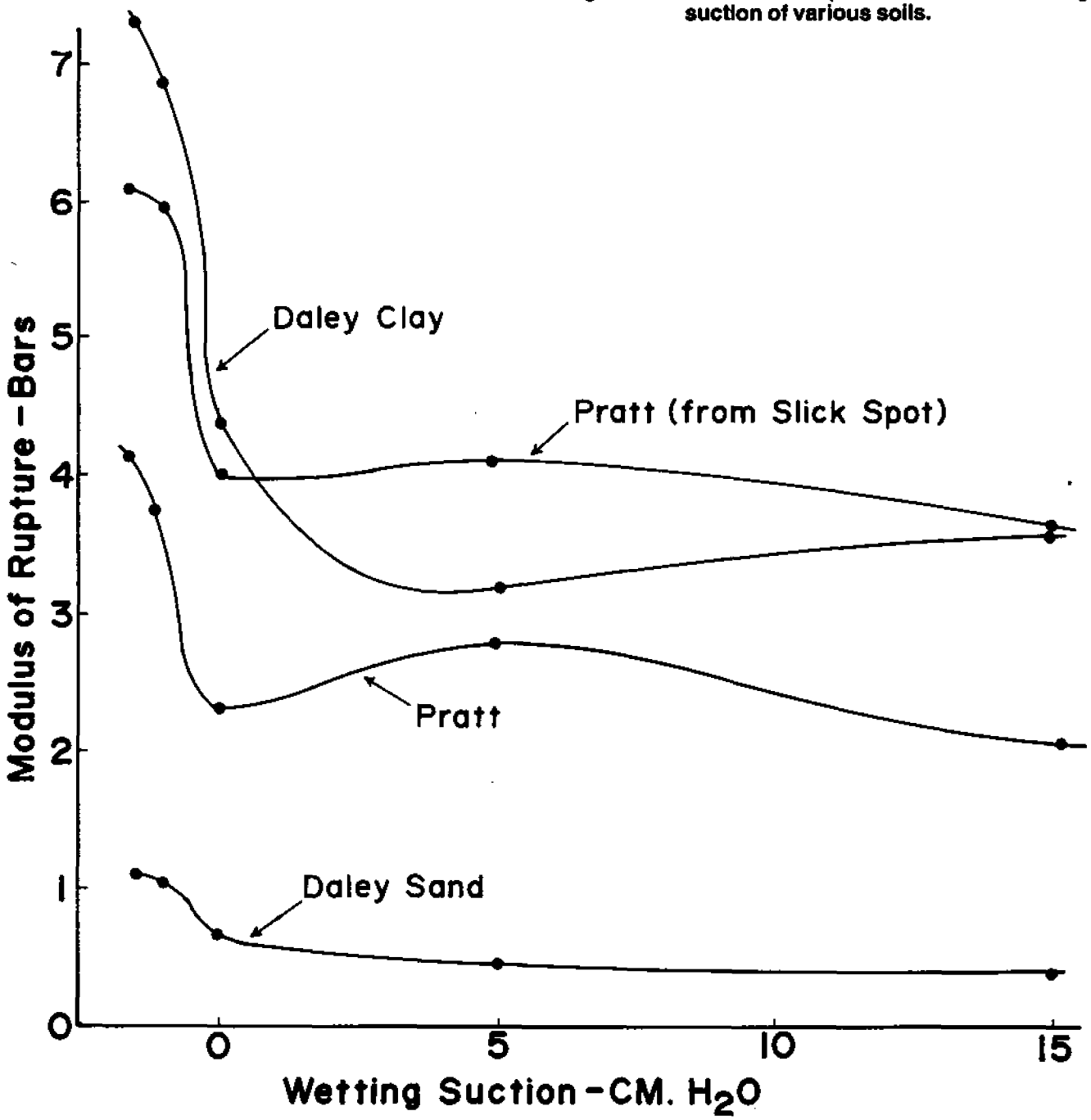
Figure 4-2. Modulus of rupture as a function of soil water content at the time of rupture (data from Kemper, Olsen, and Hodgdon, in press).



The method and rate of wetting, as well as the degree of saturation, may have large effects on crust strength. Evans (unpublished data, D. D. Evans) wet soils at 40 cm of water tension, then reduced the tension to values from 15 to −1.5 cm (water standing on the surface) and then dried the briquete and determined the moduli of rupture using the Richards (1953) technique. The results shown in Figure 4-3 indicate little effect of the final tension, unless the final tension was less than 0, i.e., the soil was flooded. Flooding the soil markedly increased the moduli of rupture on all four of these soils. Evans (1954) also showed that wetting only to the moisture equivalent resulted in more aggregate stability than when aggregates were settled to higher water contents.

The increase in modulus of rupture occurring when

Figure 4-3. Modulus of rupture versus final wetting suction of various soils.



the soils are saturated is probably due to the elimination of the air-water interphases within the sample. The tension in the soil water is equal to the pressure in the air phase minus the pressure in the water phase. This difference in pressure supports aggregates and holds them out of the large pores which are still filled with air at that tension. When the soil is saturated, water fills these large pores and the aggregates are free to "slump" into them. Since these large pores are zones of weakness, their loss results in an increase of the modulus of rupture.

If the large size pores remain intact, during drying they allow the air phase to enter the crust at relatively low tensions, so the compacting force of the drying tension pushes small amounts of sloughed soil material back out of these larger pores. The overall pressure tending to compact the whole crust layer into a denser configuration is appreciably reduced.

Keller (1967) and Ghavami (1966) applied water to soils by sprinkling at controlled rates. In general, they found that when soils are wet more slowly, the large size pores were more persistent. Kemper and Koch (1966) found that stability of wet aggregates was increased when aggregates were wet more slowly. Two major mechanisms appear to be involved in the destruction of large aggregates and pore space by rapid wetting and their effects can be observed during wetting of large aggregates (0.5 to 1.0 cm diameter). If an aggregate of this size is placed in a beaker and flooded quickly with water, the perimeter of the aggregate becomes wet before the inside and air is entrapped in the interior of the aggregate. As water continues to be drawn into the interior of the aggregate, this air is compressed and its pressure builds up until it finally breaks out one side of the water-weakened aggregate and appears as an air bubble. When the aggregate is from a weakly structured soils, practically the whole aggregate appears to disintegrate as this bubble bursts out.

The other destructive force may be observed by placing pieces of blotting paper in each of two beakers, placing large soil aggregates on each of the pieces of blotting paper, and then wetting the aggregates at different rates by pouring water down the side of the beaker rapidly (so a film of water about 1-mm thick stands on the blotting paper) and slowly (so the aggregate takes at least 10 minutes to become wet). Under the fast wetting, the bottom side of the aggregate becomes saturated while the top is still dry. Since most soils swell appreciably on wetting, this differential expansion across the aggregate causes large shearing stresses at the wetting front where water content goes from dryness to practically saturated over a distance of about a millimeter. Under the slowly setting condition, this gradient in water content as swelling is greatly reduced. Observation, or a quantitative technique such as gentle, wet sieving, will generally show that greater stresses during rapid wetting caused more weakening of the aggregate, allowing more disintegration.

To evaluate the effect of wetting method on moduli of rupture, Kemper et al. (1974) wet soils in cylinders 6 cm long and 3 cm in diameter by capillarity (wet within 3 hours) and by immersion (wet from bottom within 5 seconds). A third treatment involved wetting the samples by capillarity and then raising the water level so they were immersed. The samples were all drained and dried at 65° C. The dried soil cores were then removed from the lucite cylinders and their moduli of rupture were determined using the procedure of Kirkham et al. (1958). Figures 4-4 and 4-5 show the effects on modulus of rupture of these different methods of wetting on poorly structured and well structured soils with different amounts of organic matter, using all the soil aggregates smaller than 6.7 mm (Figure 4-4), or aggregates between 3.9 and 6.7 mm (Figure 4-5). From these data, it is apparent that method of wetting prior to drying is a major determinant of modulus of rupture or crust strength. Higher moduli of rupture of immersed samples when the smaller soil fraction was missing (compare Figures 4-4 and 4-5) is probably due to the fact that water moved into these samples more quickly, trapping some air in the large aggregates and causing more disintegration. The vertical lines with cross bars at the top and bottom in Figures 4-4 and 4-5 represent the 95% probability intervals of these average modulus of rupture values.

Comparison of the soils wet by capillarity (C) and those wet by capillarity followed by immersion (C + I) in Figures 4-4 and 4-5 illustrates the fact that removal of the air phase during wetting does increase the modulus of rupture, as discussed earlier.

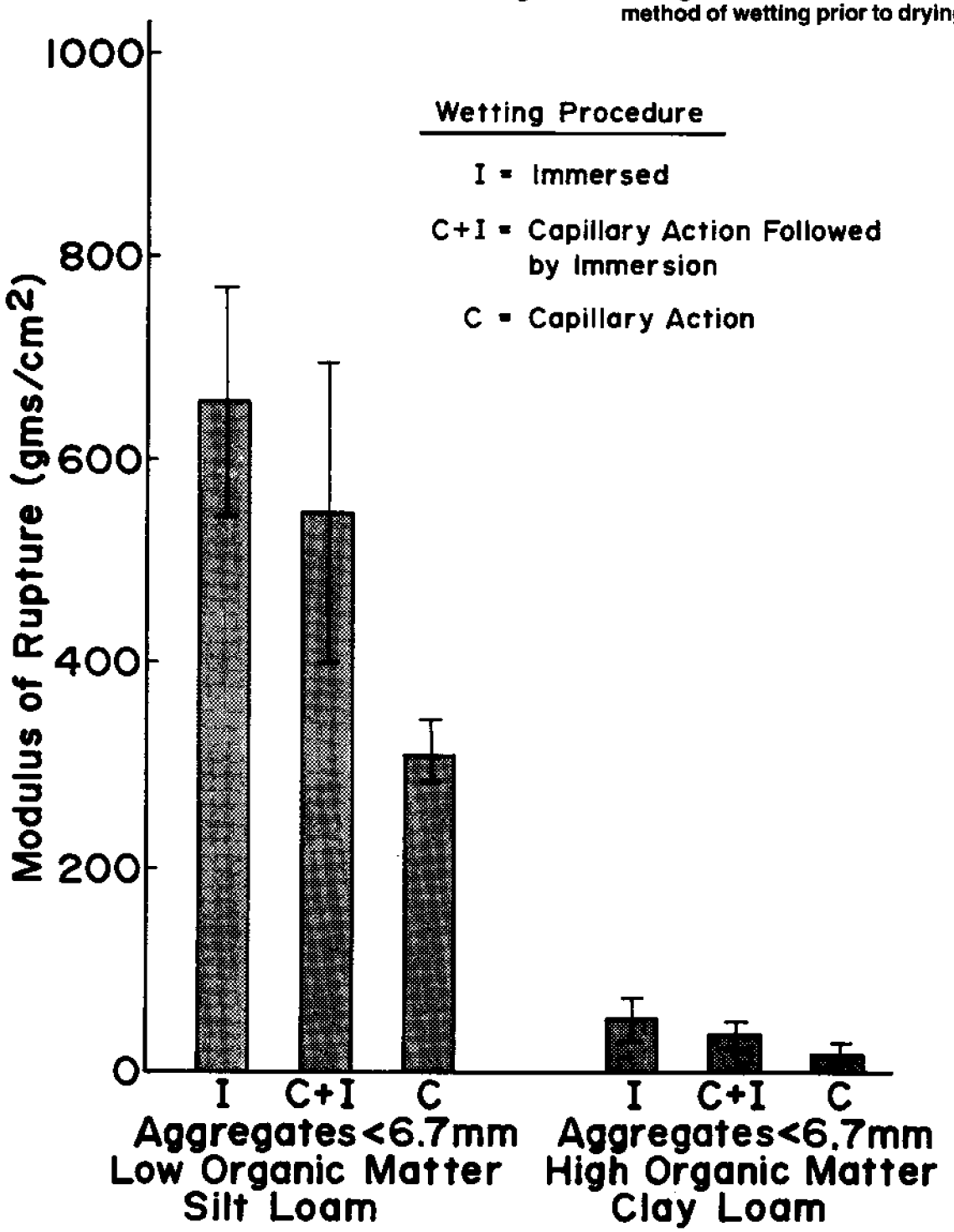
While most of the decrease in large size pores due to wetting occurs during the first wetting and drying cycle, the second and third wetting and drying cycles also result in small decreases. Strength of soil crusts increases as large size pore space is decreased.

Another factor noted by Gifford, Thran (Chapter 3) and W. D. Kemper (unpublished data) is the increasing cementation together of sand or glass particles when subjected to repeated cycles of wetting and drying. This cementation takes place even in clean acid-washed sands. The silica sand (or glass beads) have a finite solubility of the order of 10 to 30 ppm in water, which is dissolved from the particle surfaces as distilled water or rain enters the soil. When water was evaporated from these sands, the solution became supersaturated with silica. Continued drying drew the air-water menisci toward the particle-to-particle contact, depositing most of the formerly dissolved silica at the particle-to-particle contacts where it acted to cement the particles together. Twenty to 30 cycles of wetting and drying were generally sufficient to form a continuous crust on the surface of a sand. Figure 4-6 (unpublished data from W. D. Kemper) shows the cumulative effect of repeated wetting and drying cycles on this cementation.

These observations were made on simple sand or glass bead systems where the cementing component

was known and the cementation process was easily observed with a common microscope. It seems probable that similar cementations take place with other slightly soluble compounds such as $CaSO_4$, $CaCO_3$, and other carbonates, oxides, and hydroxides as soils are wet or dried. Whether this cementation is cumulative with successive wetting and drying cycles probably depends on the degree to which the soil swells and shrinks, and thereby disrupts such cementation. A large measure of the crust strength that is observed to develop in silty and sandy soils on repeated wetting and drying is probably due to this cumulative type of cementation.

Figure 4-4. Strength of dried soils as affected by method of wetting prior to drying.



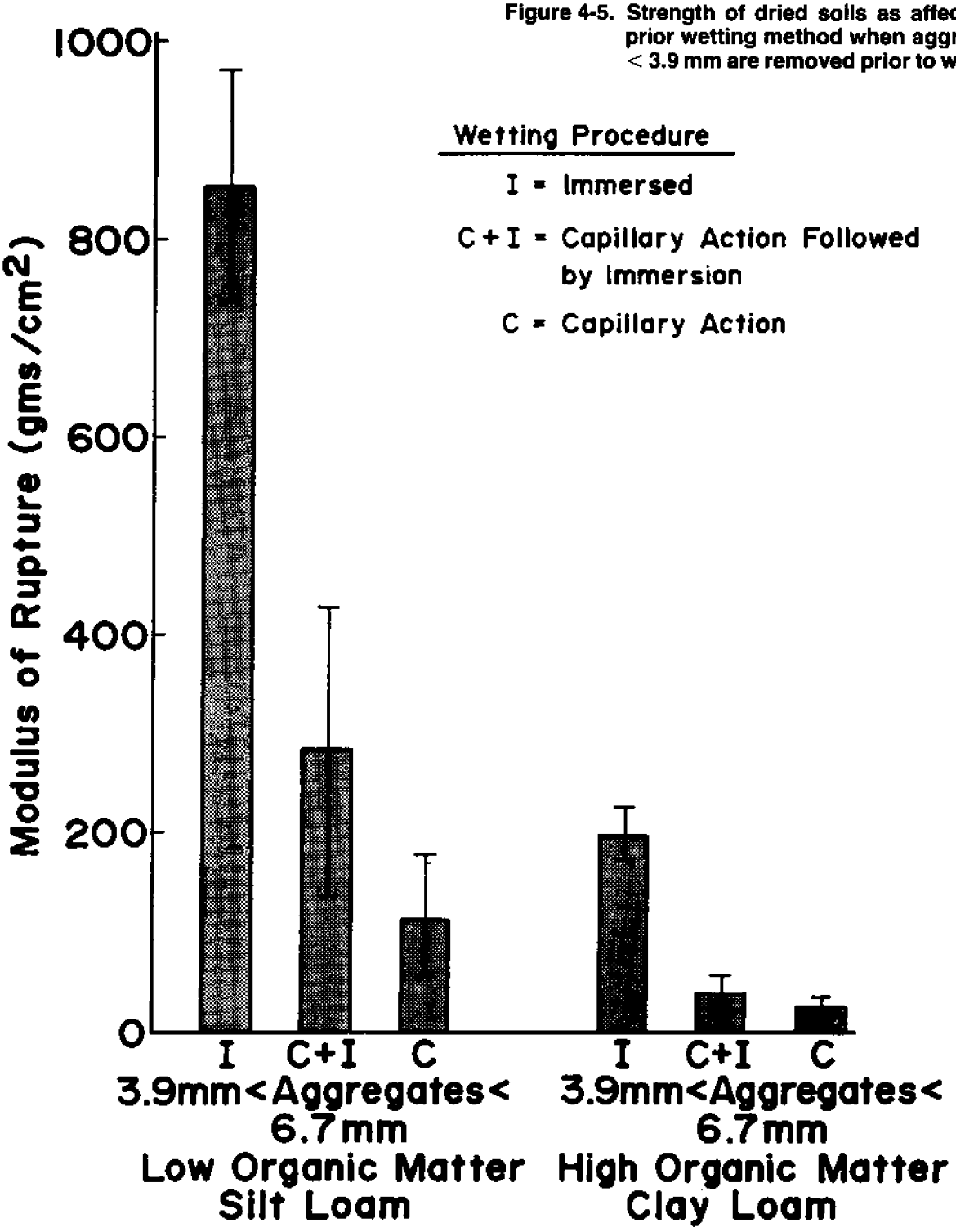
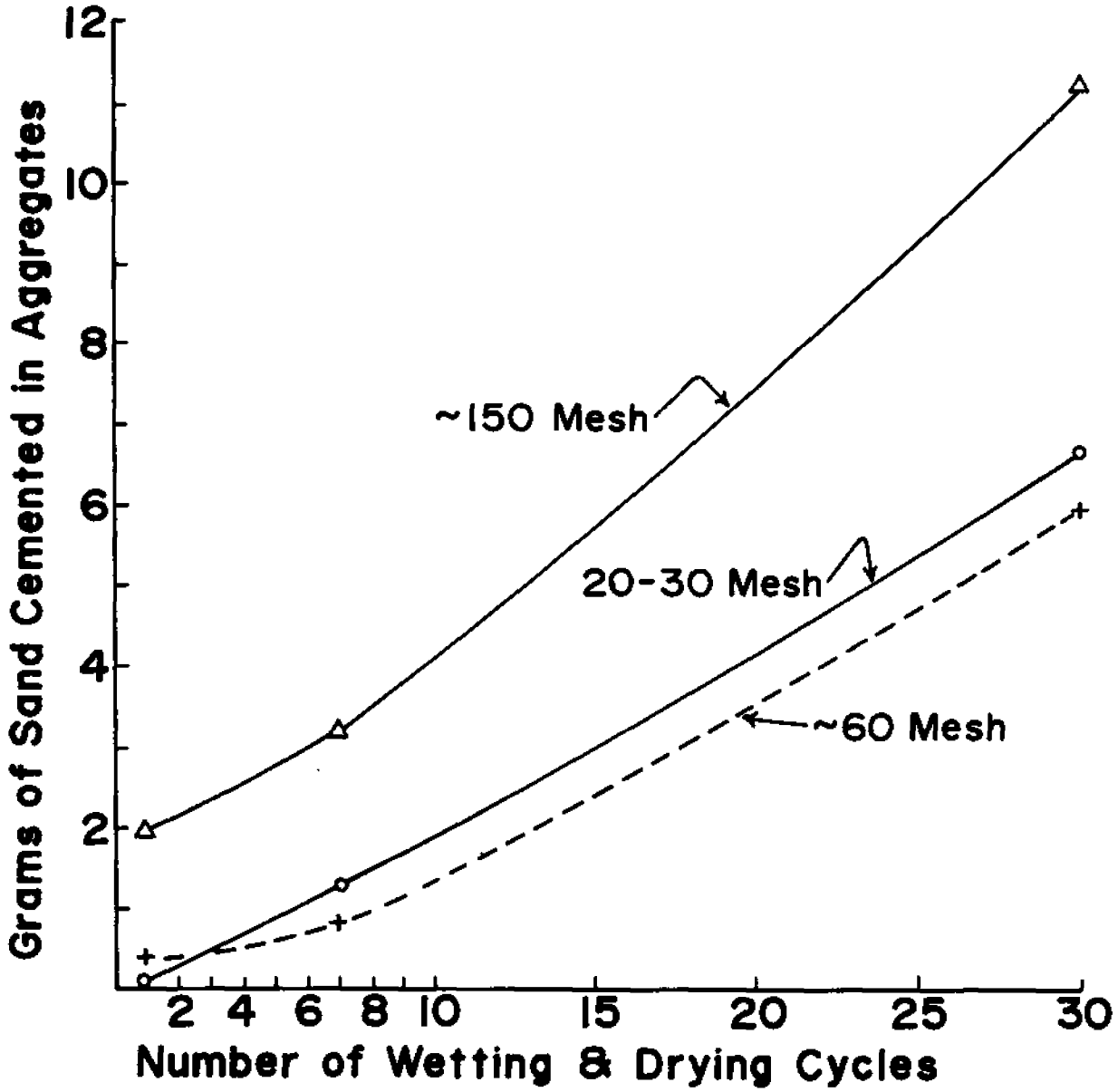


Figure 4-5. Strength of dried soils as affected by prior wetting method when aggregates < 3.9 mm are removed prior to wetting.

Figure 4-6. Sand cemented into crust segments and aggregates by dissolved and recrystallized silica as a function of the number of wetting and drying cycles. Container was 7 × 7 cm, and contained 200 gms of sand.



Crust Strength and Cracking:

PART II.

Cracking

Ronald W. Rickman

Theory

All physical properties of solid materials are more easily described if mathematical models are available for quantitative representation of the particular property of interest. Cracking is no exception. The cracking or rupture theory first proposed by Griffith (1920) is still used for a first approximation of cracking or failure in many materials. Some alternative cracking theories have been developed since that time, and additions to Griffith's theory have been proposed. The original form, however, as presented by Griffith, has been derived from both thermodynamic and statistical mechanics considerations and remains the most widely used cracking theory (Anderson, 1959). A complete explanation of Griffith's theory and an explanation of its application to soil was presented in a Ph.D. thesis by Briones (1969).

Griffith's theory considers two separate energy terms and the balance between them for determining the presence or absence of cracking. One term is the strain energy which is released by the formation of a crack. The other is the free surface energy due to the formation of new surfaces by the cracking. The amount of surface energy gained by exposure of new surface area is given in equation 4-2:

$$\frac{dU}{dA} = 2T \qquad [4\text{-}2]$$

where U is energy of the medium under consideration, A is the area exposed by a new crack and T is the surface tension of the material. The energy released per unit area by the cracking is given in equation 4-3:

$$\frac{dU}{dA} = \frac{\pi \sigma^2 c}{E} \qquad [4\text{–}3]$$

where σ is the tensile stress normal to the plane of the crack, c is the major diameter of the crack, which is assumed to be elliptical, and E is Young's modulus of the material. Cracking occurs when the release of energy per unit area by the crack (equation 4-3) is greater than the increase of surface energy (equation 4-2).

Equations 4-2 and 4-3 can be combined and solved for the limiting stress, σ_c, that will cause crack propagation. This stress is shown in equation 4-4, which is known as the Griffith formula:

$$\sigma_c = \left(\frac{2\,ET}{\pi\,c}\right)^{1/2} \qquad [4\text{–}4]$$

Irwin (1957) suggested modifying the Griffith formula slightly to make it more applicable to plastic materials (those materials which exhibit measurable deformation before rupture). Deformation is considered to begin in plastic materials when limiting stress is applied, but may or may not result in cracking. When $\sigma = \sigma_c$, equation 4-3 defines the critical strain-energy release rate (G) shown in equation 4-5. G is said to represent a fundamental property of the material in the same sense that modulus of elasticity is a fundamental property.

$$G = \frac{\pi \sigma_c^2\, c}{E} \qquad [4\text{–}5]$$

The application of equation 4-5 to the solid materials for which the equation was developed is simpler than its application to soil crusts. For solid materials, σ_c can be determined from applied stress on a specimen just before rupture; c may be determined from either known impurities, crystalline structures of the material, or inscribed scratches; E is a constant at constant temperature for the material. In soils, both σ_c and E vary with water content and bulk density; c is an unknown quantity which might be estimated from pore size distributions or grain sizes. Briones has suggested that it may not be necessary to evaluate c for soils. Perhaps the ratio G/c is sufficient to characterize soil cracking behavior. G/c is the energy released per unit area per unit length of crack and has dimensions of dynes per square centimeter. If this ratio is sufficient to characterize cracking behavior, it leaves only the terms σ_c and E to be evaluated. Some examples of G/c values for three Hawaiian soils are presented in Table 4-1:

Table 4-1. Critical strain-energy release rate per unit of preexisting crack (G/c) in the soil samples at various tensions. Taken from Ph.D. thesis by Briones (1969). All three soils are clays. The Wahiawa and Molokai have kaolinite as the clay mineral. The Luaiuaiei has montmorillonite clay minerals. A-desorbing samples; B-samples dried at 71% relative humidities, then equilibrated at respective humidities.

Relative humidity	Wahiawa		Molokai		Luaiuaiei	
	A	B	A	B	A	B
%						
98	0.47	0.22	0.49	0.13	4.94	2.08
71	0.53	0.16	0.35	0.11	3.16	4.03
51	0.09	0.06	0.08	0.09	1.38	0.03
31	0.07	0.07	0.12	0.10	3.25	0.001
10	0.12	0.03	0.15	0.09	0.08	0.000

The soil with the greatest tendency to crust contained primarily montmorillonitic clays. The other two soils contained kaolinitic clays. The G/c values are considerably greater for the crusting soil.

One way to determine σ_c is from standard modulus of rupture measurements on soil briquets. The modulus of rupture is the maximum tensile stress developed in a briquet at rupture. The method for computation of σ_c was presented by Allison (1923) (equation 4-6).

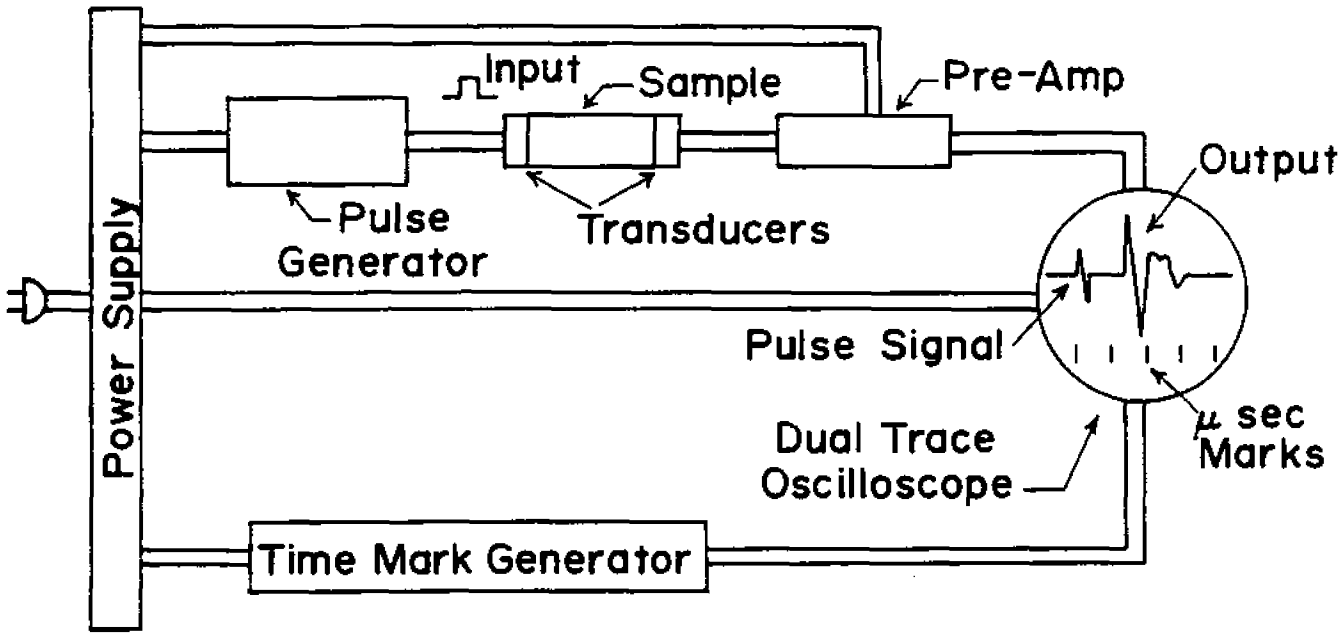
$$\sigma_c = \frac{3\,FL}{2\,bd} \qquad [4\text{–}6]$$

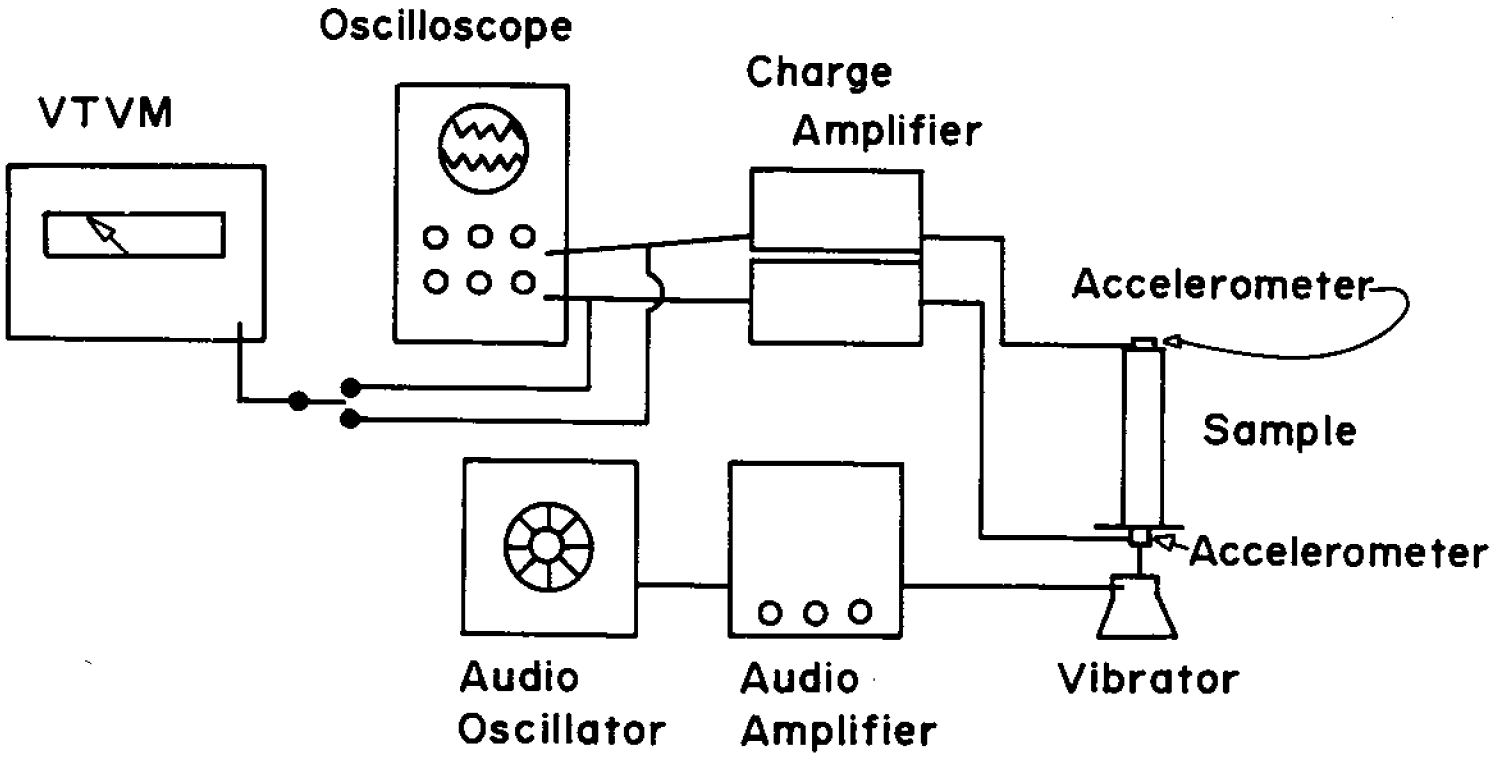
where F is the breaking force in dynes (grams × 980), L is length between end supports of the modulus of rupture apparatus, b is briquet width, and d is briquet thickness.

Values for E are not as readily available as are values for σ_c for agricultural soils, even though both static and dynamic techniques are available for measuring E of soil samples. Measured values of E available in the literature are restricted primarily to highly compacted soils which were to be used for engineering purposes. Two reasons have led to this situation. Highly compacted soils respond in a more nearly elastic manner than uncompacted soils, and there is a major demand for engineering data for using compacted soils in construction.

It appears that dynamic measurements will prove valuable in obtaining modulus values for agricultural soils. Briones describes the use of pulse transmission equipment diagrammed in Figure 4-7 for determining sample modulus values. Others who have used this technique in the laboratory are Baker and Triandifilidis (1967), Hampton and Wetzel (1967), Osgood and Green (1966). Hobson and Hunter (1969), and Bamert et al. (1967) have used this principle for field investigations. In its simplest form, the equation used to deter-

Figure 4-7. Schematic diagram of ultrasonic test equipment for measurement of pulse velocity in soil samples (Briones, 1969).





mine elastic moduli from pulse transmission velocity measurement is given in equation 4-7:

$$E = \rho v^2 \qquad [4\text{–}7]$$

where ρ is soil density (including water), and v is pulse transmission velocity.

The essential requirements for use of equation 4-7 are (a) an assumption that the soil behaves elastically, (b) a pulse or wave source, (c) a method for timing the rate of travel of the pulse or wave between two points, and (d) one must also either assume he is timing compressional waves (in contrast to shear waves) or correct equation 4-7 for the different type of or combination of waves that are timed. Briones (1969) discusses this matter in more detail.

Direct wave or pulse velocity measurement has a serious disadvantage for application to agricultural soils. The energy of a pulse is very rapidly absorbed in a noncompacted or low bulk density soil. It is, therefore, difficult to accurately measure pulse velocities in uncompacted soils or uncompacted soil samples.

There is another dynamic measurement technique that can be used in a laboratory to determine modulus values of noncompacted soil samples. A resonant frequency technique for measuring moduli of soil columns was developed by Lee (1963). Modulus values for low bulk density soils were measured with this technique on equipment shown in Figure 4-8. The frequency of vibration of the vibrator was varied until the ratio of movement of the top of the soil column to the movement of its bottom became a maximum. The frequency at which this occurred was termed the resonant frequency (f) of the column and is used in equation 4-8 to calculate the modulus of the soil column,

Figure 4-8. Equipment and sample arrangement for measurement of sample column resonant frequency for calculation of elastic or viscoelastic modulus (Rickman, 1970).

$$E = 16 f^2 H^2 \rho \qquad [4\text{–}8]$$

H is the column length and ρ is column density. Figure 4-9 shows the change of elastic modulus with water content of some soils as measured with this equipment (Rickman, 1970). The resonant frequency technique provides modulus information for uncompressed soils and provides the opportunity to extend measurements of soil moduli to low bulk density ranges.

Figure 4-10 presents data obtained by Briones (1969) on the variation of E in compacted soils as a function of both water content and density. The type of data shown in Figures 4-9 and 4-10 and Table 4-1 is needed to utilize Griffith's cracking theory to predict the occurrence of cracks as a function of soil water content. The magnitude of change in both G/c and the moduli with water content and density illustrate the importance of knowledge of this variation for proper cracking analysis. For the soils in which cracking be-

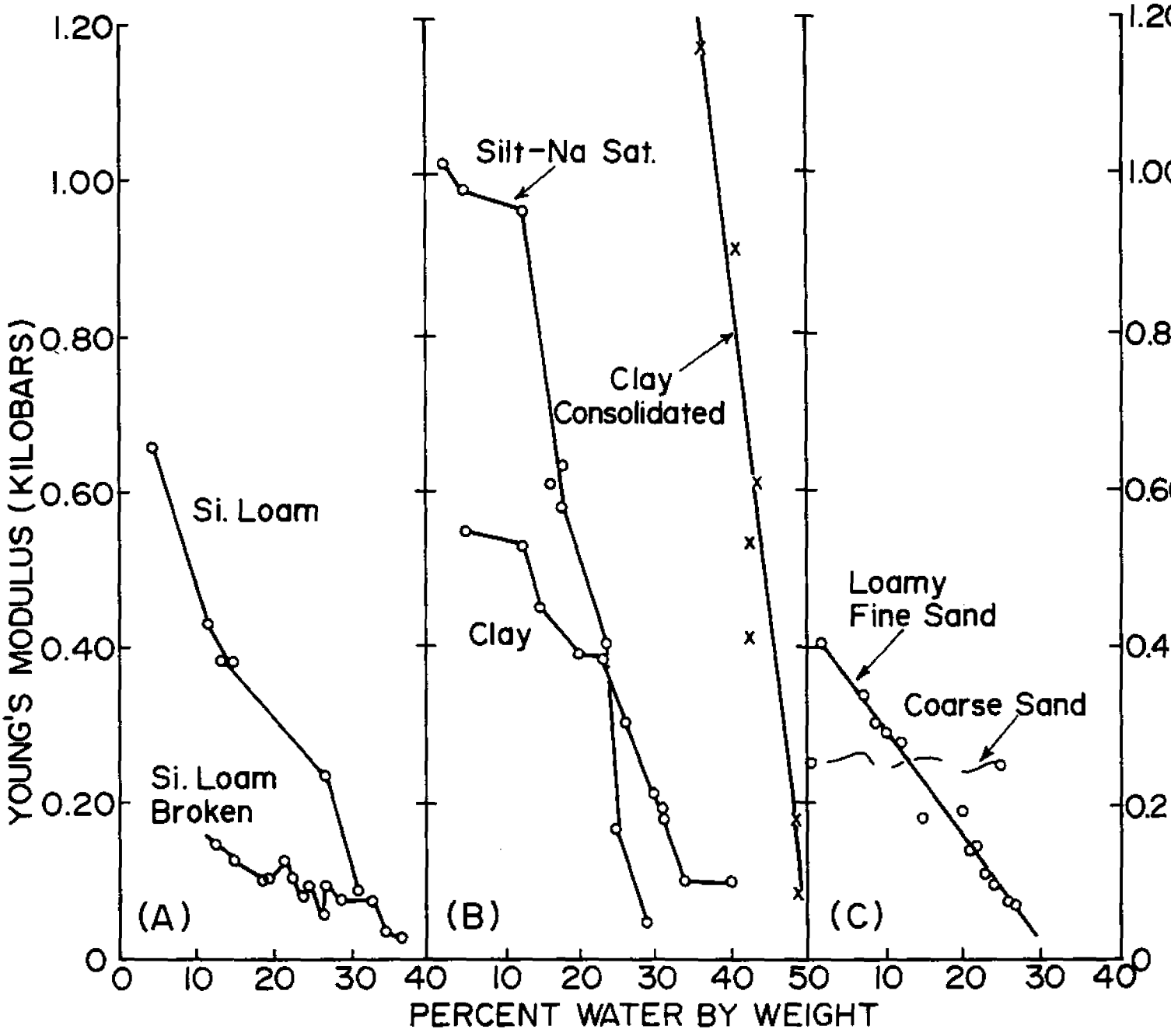
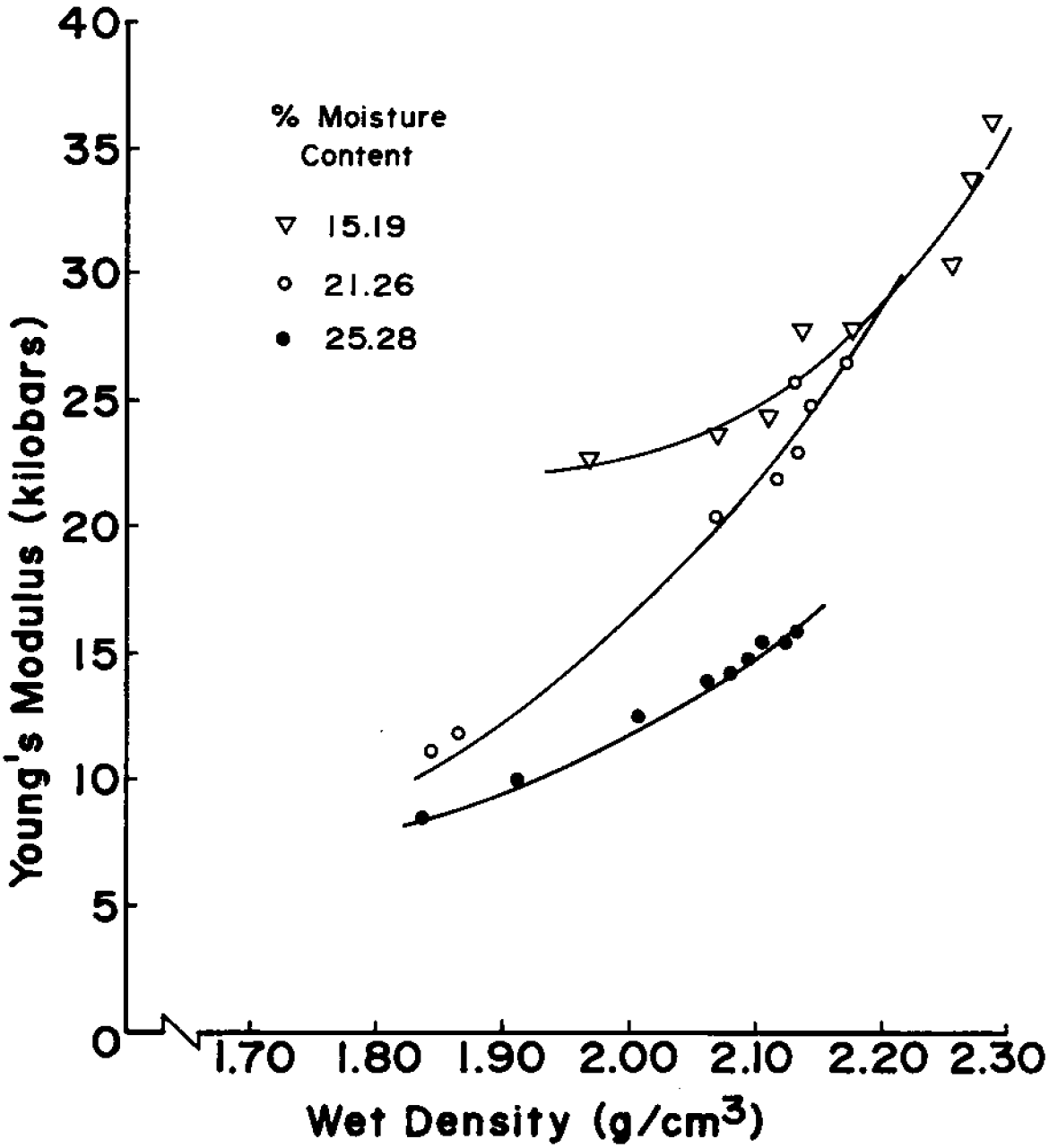

YOUNG'S MODULUS (KILOBARS)
1.20
1.00
0.80
0.60
0.40
0.20
0
Si. Loam
Si. Loam
Broken
(A)
Silt-Na Sat.
Clay
Consolidated
Clay
(B)
Loamy
Fine Sand
Coarse Sand
(C)
0 10 20 30 40
10 20 30 40 50
10 20 30 40
PERCENT WATER BY WEIGHT

Figure 4-9. Young's modulus *vs* water content for soil columns. In section A, (Si Loam) data were for a silt loam subsoil and the (Si Loam Broken) column was made from ½ mm Portneuf silt-loam aggregates. In section B, the clay was from the B horizon of a soil collected in Idaho, and (Silt-Na Sat.) a Na-saturated silt from Nevada. In section C, (Coarse Sand) was a washed (1 mm) sand and the loamy fine sand was from Idaho. Data for undisturbed cores of a consolidated clay subsoil collected by Ishimoto and Iida (1936) were included (in section B) to provide a comparison with the reported measurements (Rickman, 1970).

Figure 4-10. Influence of wet-bulk density and water content on Young's modulus in the Luaiuaiei soil materials (Briones, 1969).



havior is usually most important (clays and silts), water content has a major effect on modulus values.

Once the values for elastic modulus and critical stress have been established as functions of water content and density, equation 4-9 may be used to predict the occurrence of cracking as a function of soil-water content (θ).

$$\sigma'(\theta) < \left(\frac{\frac{G}{c}(\theta)\, E(\theta)}{\pi} \right)^{1/2} \qquad [4\text{–}9]$$

The notation(θ), following previously defined terms, indicates the dependency of these terms on changes in the variable θ, in this case water content. If $\sigma'(\theta)$ remains smaller than the square root term in equation 4-9, no cracking is expected. Only when tensile stress exceeds the critical value is cracking expected. In a drying soil, $\sigma'(\theta)$ may be approximated by soil-water matric potential. Through the moisture release curve for a soil, water content and tensile stress on the crust of a drying soil are, therefore, related.

Application of the Theory

There are sufficient elastic modulus data available for soils in general to project the range over which they may vary. The degree to which these modulus values may be altered by management practices has not been established, however. Considerable information should be available from modulus of rupture measurements to enable calculation of critical energy release values for soils. For "quantitative" analysis of a specific soil, however, both measurements—modulus of rupture and elastic modulus—as functions of water content and bulk density, will have to be made on that soil. The effect that E and G/c values have on occurrence of cracking is evident from equation 4-9. In equation 4-9, these two terms combine as a product. The larger E or G/c becomes, the less the tendency for the soil to crack (more prone to crust). Observe in Figure 4-8 the uncompacted soil with the largest E (the sodium saturated silt) has the greatest crusting tendency. In Table 4-1, the soil with the greatest tendency to crust (the Luaiuaiei) has the largest G/c.

As stated earlier, little experience has been obtained using this cracking analysis of soil crusts to enable one to project the effects of various management practices on soil crusting behavior. Based upon the equations from the theory, however, some general statements may be made about factors which would be expected to increase soil cracking or decrease the tendency of the soil to crust over. First, consider equation 4-9. If the soil is to crack, the product of the two terms G/c and E must be made as small as possible. From equation 4-5, it can be seen G is dependent on the square of σ_c, the critical stress of a soil. In equation 4-4, it can be seen that σ_c is dependent upon the surface tension (T) of the soil, the initiating crack diameter (c), and Young's modulus E. Based on equation 4-4, one might expect a detergent or wetting agent that would reduce the surface tension of water, which is effectively the surface tension of a wet soil, would decrease a soil's tendency to crust or increase its tendency to crack. Similarly, any method that would increase the size of voids from which cracks may begin, should increase a soil's cracking tendencies. Conversely, any practice that will decrease the size of pores in a soil would be expected to decrease its cracking tendencies, and therefore increase its tendency to crust.

An example of a management practice that is used to reduce crusting is the addition of straw or crop residues to a soil. Only when this material remains projecting through a soil surface and thereby increases the effective c would it be expected to increase the cracking tendency of a soil surface crust. The effect of this added residue or mulch upon E has been ignored in the previous statement. There is presently no data available on the effects of management practices such as mixing the crop residues on the modulus value (E) of the soil. Such a practice might be expected to reduce the modulus somewhat, and therefore increase the tendency for a soil to crack.

One further consideration should be made in the analysis of soil crusting. One major reason for the study of soil crusting is the prevention of seedling emergence caused by soil crusts. In addition to the stress caused by soil water, the stress imposed by a growing seedling should be included in a specific analysis for prediction of seedling emergence through a crust. Since, as shown in Chapter 2, the emergence pressure of different seedlings varies considerably, one should be able to predict the emergence of some crops under a particular crust, while others would not be expected to emerge through the same crust.

In summary, the application of Griffith's cracking theory to soils requires that material properties used in the theory (elastic modulus and critical energy release rate) be measured as a function of water content and density of a soil. Sufficient data for these properties of soils are available to project the range over which each may vary for soils; however, measurements of both parameters and the entire range over which they vary for a specific soil have not yet been made. The modulus of rupture technique appears to be sufficient to obtain energy release rate. There are several techniques available to obtain elastic modulus for soils. Static methods may be used for highly compacted soils in the laboratory or in the field for uncompacted soils. The equations of cracking theory permit speculation on the influence of various management practices on soil crusting behavior.

• CHAPTER 5

The Influence of Soil Crusts on Heat and Water Storage

John W. Cary and Daniel D. Evans

There is a continuous exchange of water, air, and heat between the soil and atmosphere. This has a profound influence on weather, plant growth, and ground water storage. Increased advective energy transport and air turbulence are often consequences of heat exchanged between the soil and the atmosphere. The release of heat from a firmly packed soil which makes crop plants less apt to be frozen than those growing on a loose, recently cultivated soil is another example. The interchange of water between soil and atmosphere also profoundly affects our environment. If water reaches the soil surface faster than it can be absorbed, runoff and flooding occur. Water absorption by the soil is a basic requirement for ground water recharge and, consequently, necessary for the continued flow of all springs and wells. Taken from this veiwpoint, the exchange of heat and water through soil crusts is of quite general interest.

Heat and Water Vapor Flux through Soil Crusts

The important variables

Most of the energy arriving at the soil surface comes from the sun in the form of electromagnetic radiation. Once a portion of its radiation is absorbed by the surface and is converted to kinetic energy, it may be transported into the soil by molecular thermal conduction or as latent heat, the process being described as

$$J_H = -\lambda \nabla T + L J_v \qquad [5\text{–}1]$$

where

$$J_v = -D \nabla C + CV \qquad [5\text{–}2]$$

and J_H is heat flux, J_v vapor flux, D the apparent diffusion coefficient of water vapor in soil air, C the concentration of water vapor in the soil air, V the average net velocity of air through the soil pores, L the latent heat of vaporization, T the temperature, and λ the molecular thermal conductivity.

The relative magnitudes of each of the two terms in equation 5-1 can be estimated. Consider, for example, a bare surface receiving radiant energy from the sun such that a gradient of 5° C/cm occurs in the surface, as reported by Rose (1968). Under these conditions, a reasonable value for the thermal conductivity is 1 to 3 mcal(sec cm °C)$^{-1}$, giving a molecular conduction heat flux of 0.3 to 0.9 cal (cm^2 min)$^{-1}$ for the first term in equation 5-1. Assuming that the soil near the surface is damp enough (wetter than -15 bars) so that the relative humidity is near 100%, the vapor flow resulting from diffusion may be calculated for the second term in equation 5-1 as

$$J_v = \beta\,(1.56 \times 10^{-5} T^2 + 2.72 \times 10^{-3})\,\nabla T \qquad [5\text{–}3]$$

where β is taken as 2 (Cary, 1966) and J_v = mm H_2O/hr, assuming the average temperature, T, to be 35° C. Multiplying by the heat of vaporization, one gets

about 0.2 cal$(cm^2\ sec)^{-1}$. Even very light wind above the soil surface can cause convective transfer of air in the soil surface layers, doubling the diffusive water vapor flux and causing values of LJ_v to be as large as 0.4 cal $(cm^2\ min)^{-1}$ (Scotter and Raats, 1969).

The concentration of water vapor in the air is almost entirely controlled by the temperature when the soil moisture tension is less than 25 bars. Under drier conditions, concentration of water vapor is jointly controlled by the temperature and the amount of water and soluble salt in the soil. The effective diffusion coefficient of water vapor through the soil depends on the cross-sectional area of pore space in the soil and is inversely proportional to the path length or tortuosity of these pore spaces.

The molecular thermal conductivity λ increases as moisture content or bulk density increase. The thermal conductivity may be measured or calculated from the volume fractions of the soil's constituents and appropriate factors given by DeVries (1963).

The amount of shortwave radiant energy absorbed by the soil and converted to kinetic energy depends on the soil surface reflectance. Energy absorption is favored by large particles, rough surfaces, high moisture contents, and by dark surface colors. The radiant energy absorbed at the soil surface raises the temperature of the soil particles. These particles, in turn, transfer heat to the air around them and conduct heat downward into the cooler soil mass.

As heat moves downward and the soil temperature rises, vapor pressure of the absorbed water rises and it begins to diffuse in the vapor phase both up toward the lower vapor pressures in the air above the surface and down toward the lower vapor pressures in the cooler soil below. The upward diffusion rate will generally be less than 1 mm H_2O/day, while the downward diffusion rate may run about half this amount (Cary, 1967a).

Gentle winds or convective heat transfer in the air above the surface cause turbulence and pressure changes in the first few cm of soil which create viscuous flow of gas in the open soil pores. This increases the transfer of water vapor and, consequently, the flow of latent heat. Increasing the density of the soil reduces the viscuous flow of air and latent heat since viscuous flow is proportional to the square of the pore radius so long as the flow is laminar and the pore area is constant. On the other hand, increasing the density increases the thermal conductivity of the soil and increases the flow of heat by conduction.

During the nighttime there is a net loss of longwave energy from the soil surface as it radiates to the sky. This causes an upward soil heat flux. In general, on a clear night the air will be warmer than the soil surface and so will lose heat to the soil. The upward thermal gradient in the soil also creates an upward vapor pressure gradient, causing water vapor diffusion from deeper soil toward the surface. A packed soil surface, or one with a thick crust, favors nighttime heat loss. Gradwell (1963) has reported that a bare soil with a bulk density of 0.8 lost 40 to 50 cal/cm^2 during the dark, while denser soil, 1.2 gm/cm^3, lost 58 to 89 cal/cm^2.

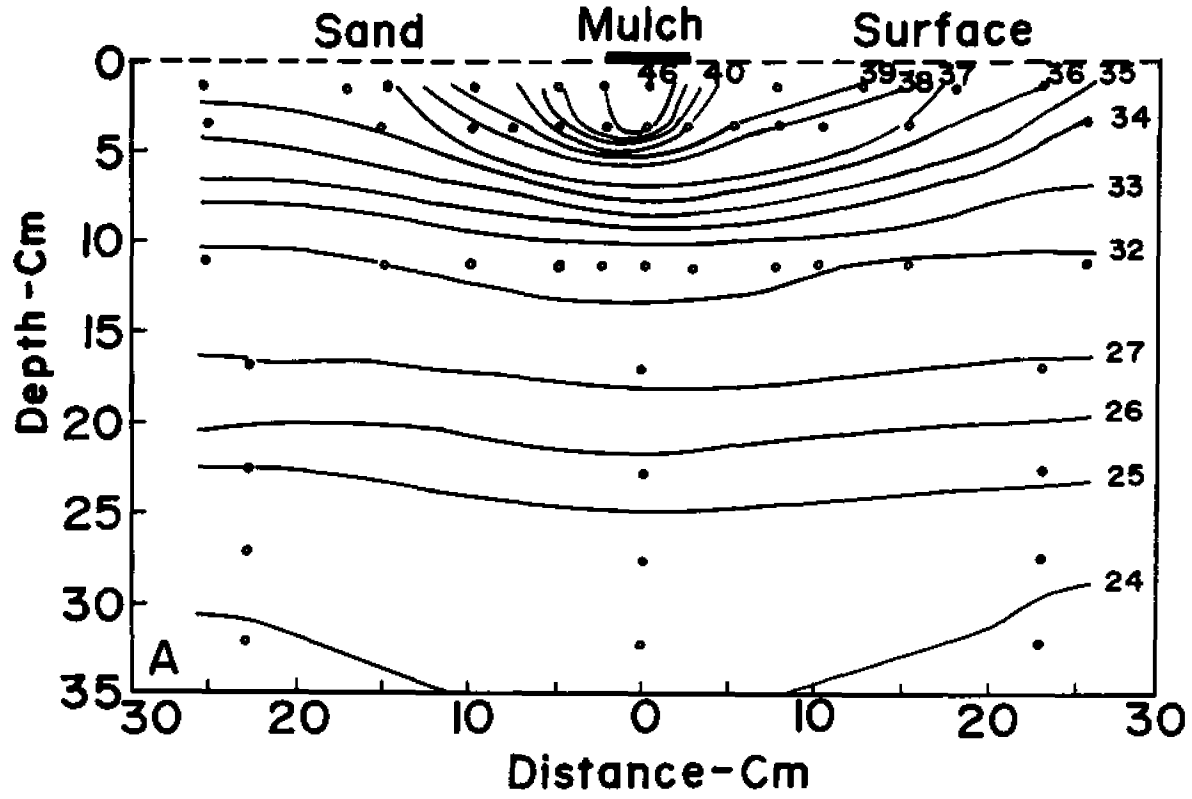
Modifying heat and vapor flow through crusts

Artificial layers such as asphalt, plastic, or gravel mulches, will strongly affect the transfer of energy between the soil and atmosphere as well as decrease crusting. Miller (1968), working at Prosser, Washington, found that an asphalt mulch sprayed in 30-cm wide strips over rows of sweet corn seed raised the daytime soil temperatures at a depth of 6.4 cm by as much as 3° C. However, nighttime temperatures on all treatments at this depth approached the same minimum. Measurements made in southern Idaho of net radiation 1.5 meters above silt loam soil with 8-cm-wide asphalt strips sprayed on 48-cm center rows showed no detectable difference from the smooth check plots.

Kowsar et al. (1969) have studied the effect of petroleum mulch on soil water content. In addition to increased soil temperatures, they found an increase in water content several centimeters below the mulch. This was evidently caused by surface sealing and a downward flux of water vapor away from the warm soil-asphalt interface. Qashu and Evans (1967) studied the effect of a black granular mulch on soil temperatures and water distribution. These treatments had a profound effect on afternoon soil temperatures (Figure 5-1), and consequently increased the heat exchange between the soil and atmosphere. Field observations showed that the soil 2.5 cm below this granular-type mulch retained more water than the control. A friable soil layer formed under the mulch, while a hard crust was formed where no mulch was present. Evidently the vapor transfer upward through the mulch was less than the net upward transfer through the dry soil crust. Because of the higher soil temperatures, the vapor pressure gradient toward the surface should have been greater under the mulch. However, the air velocity term in equation 5-2 may have been enough smaller to account for the net decrease. There was considerable cracking of the natural soil crust which could have encouraged convective transfer of the water vapor. It is also possible that differences in hydraulic conductivity were involved.

Bresler and Kemper (1970), working with columns of soil in the laboratory, demonstrated differences in drying rates which were associated with soil crusts. Soil columns were wetted by flooding, artificial rain, and

Figure 5-1. The effect of the shape of 2 black granular mulches on soil temperatures in the field. Figure A has a 5-cm wide mulch, and Figure B a 10-cm V-shaped mulch (Qashu and Evans, 1967).


Sand
Mulch
Surface
0
5
10
15
20
25
30
35
Depth-Cm
46
40
39
38
37
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35
34
33
32
27
26
25
24
A
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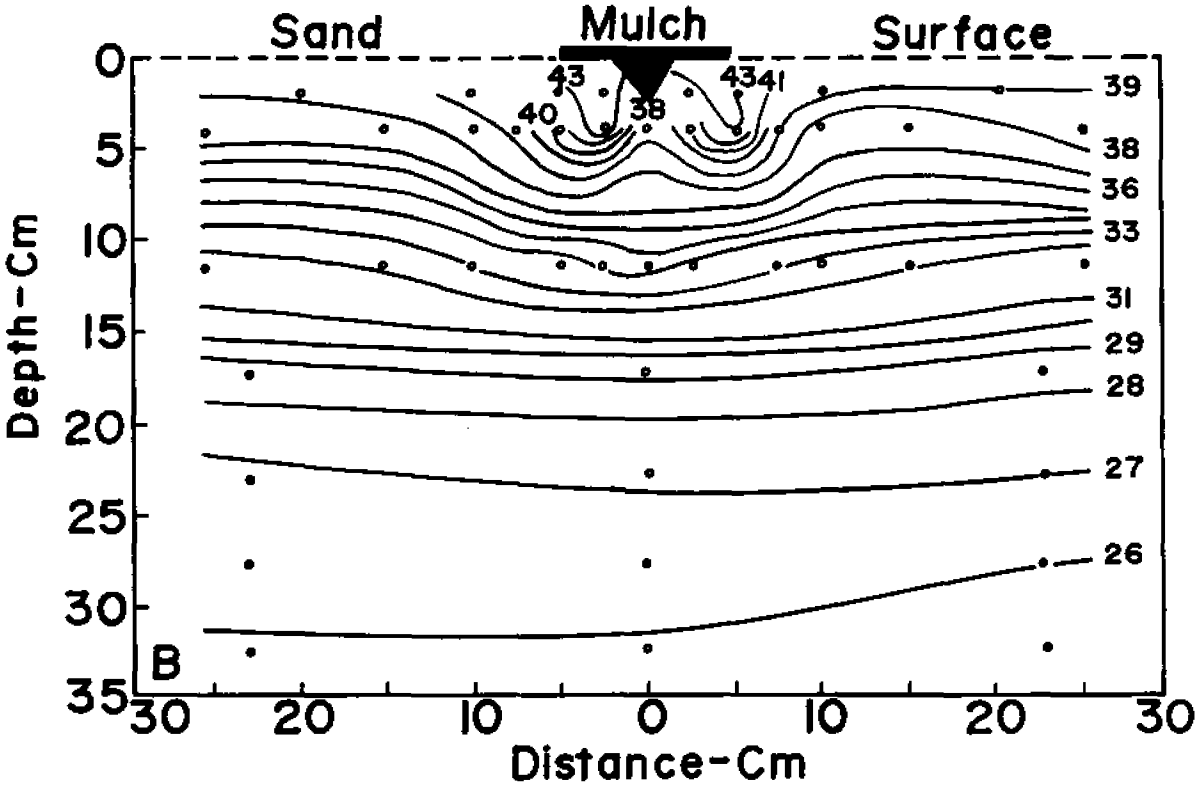
10
20
30
Distance-Cm


Sand
Mulch
Surface
0
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Depth-Cm
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31
29
28
27
26
B
30
20
10
0
10
20
30
Distance-Cm

rain with NaCl added at the surface. The columns wetted by rain formed the most severe crusts and also showed lower evaporation rates during the next few days as drying proceeded. Because the pores in the crust were generally smaller than those just below it, hydraulic conductivity was higher in the crust than at the crust-soil interface during the initial stage of drying as the larger pores at the interface began to empty. Consequently, the crust-soil interface was unable to transmit enough water to meet the evaporative demand, causing the pores in the crust to empty and dry rapidly. The dry crust then helped insulate the moist soil from the incoming heat necessary to cause evaporation.

The effects of a crust on water infiltration and its subsequent return flow toward the surface upon drying may cause significant secondary changes in evaporation through salt redistribution (Quyyum and Kemper, 1962). The water-holding capacity and hydraulic conductivity of many soils is dependent on the type and amount of salt present (Rasmussen and McNeal, 1973). Another possible effect is the concentration of salt in the air-water interface during evaporation. Evaporation rates as low as 0.5 mm/day can more than double the amount of salt at the sites of evaporation in wet soil (Cary, 1965), and the concentration may increase by an order of magnitude with greater evaporation rates. Though increasing the salt concentration decreases vapor pressure, resulting in decreased evaporation under isothermal conditions, conditions in the field are not isothermal, and when the sun's energy is not used for evaporation more heat goes to warming the soil. As the soil warms, the vapor pressure rises, and so the effect of salt accumulation on vapor pressure tends to be reduced under real field conditions. Another effect of salt, and perhaps its most important, involves the reflection of light. If, upon drying, the crust surface is covered with enough crystalline salt to give it a lighter color, the reflectance will increase and both heat and water vapor flow through the crust will decrease (Cary, 1967a).

It is possible to form a variety of crusts on the same soil by different management treatments. Cary (unpublished data) formed 4 different soil surfaces on the Portneuf silt loam by flooding, subirrigating, sprinkling, and dry mulching the soil in replicated 10-liter containers. During a period of 60 days in the field, differences in water evaporation between the four treatments were less than 10% and so within the experimental uncertainty. The average daily evaporation rate is compared to the average U. S. Weather Bureau pan evaporation in Figure 5-2. At the end of the drying period, the surface-sprinkled treatment had a dense surface crust 3 to 5 mm thick overlaying several centimeters of very dry friable soil. The treatment that had been wet only by subbing had no detectable crust and differed from the dry mulched treatment only in a denser surface. The treatment that had been flooded had a massive hard crust on the top 2 cm which had cracks about 0.5 cm wide, but only 2 cm deep.

It appears, assuming identical initial moisture conditions, soil crusts may have negligible effects (i.e., less than 10%) on water loss from the soil under field conditions, provided there is no difference in color and provided the crusts do not penetrate or crack more than 2 or 3 cm below the soil surface. However, in the event of restricted initial water infiltration, deep cracking, or dust mulches 10 cm or more deep, differences in drying will occur (Adams, et al. 1969; Papendick et al. 1973).

The effect of natural soil crusts on heat transfer was also studied on the silt loam soil at the Snake River Conservation Research Center in southern Idaho. Basins approximately 3 m^2 were formed on a field plot, and different soil crusts developed on them as shown in Figure 5-3. Soil temperatures were measured on a clear, calm afternoon in September with air temperatures in the 70's. There was no significant difference in temperatures at the 10 cm depth, but average surface temperatures during the middle of the afternoon were:

Plot No.	1	2	3	4	5
Temperature °F	94	87	89	84	90

The high temperature on plot No. 1 was caused by the low thermal conductivity of the rototilled surface. Its bulk density was only 1.04 g/cm^3. The low surface temperature of plot 4 was caused by a light-colored layer of silt which had been deposited on the surface by the irrigation water. The surface crust bulk density of all plots except No. 1 ranged from 1.5 to 1.7 g/cm^3; significant differences could not be measured because of the experimental error in volume measurements.

The crust on plot 5 was most severe. Because of extreme cracking, the soil below it had dried out more than under the other crusts. As plot 5 dried, it tended to form two layers of crust. The upper one, about 1 cm thick, tended to peel away from the lower layer of hard, massive material 4 to 6 cm thick, which showed a definite vesicular structure similar to Figure 1-1.

The crust on plot 4 was about 4 cm thick and had developed some vesicular structure 1 cm below the surface. This vesicular structure did not develop in the crusts formed by sprinkler irrigation and natural rainfall. The only obvious difference between the ponding of water on plots 2 and 4 was that the water ponded on plot 4 contained suspended silt and clay, whereas that on plot 2 remained clear. The least severe crust was formed by natural rainfall. It should be noted, too, in Figure 5-3 that the severe soil crusts reduced emergence of weeds which could ultimately have profound effects on heat and water transfer between the soil and the atmosphere.

The density of a dry soil surface is important in determining heat exchange (Allmaras et al., 1972). An example of this effect was shown with net radiation and

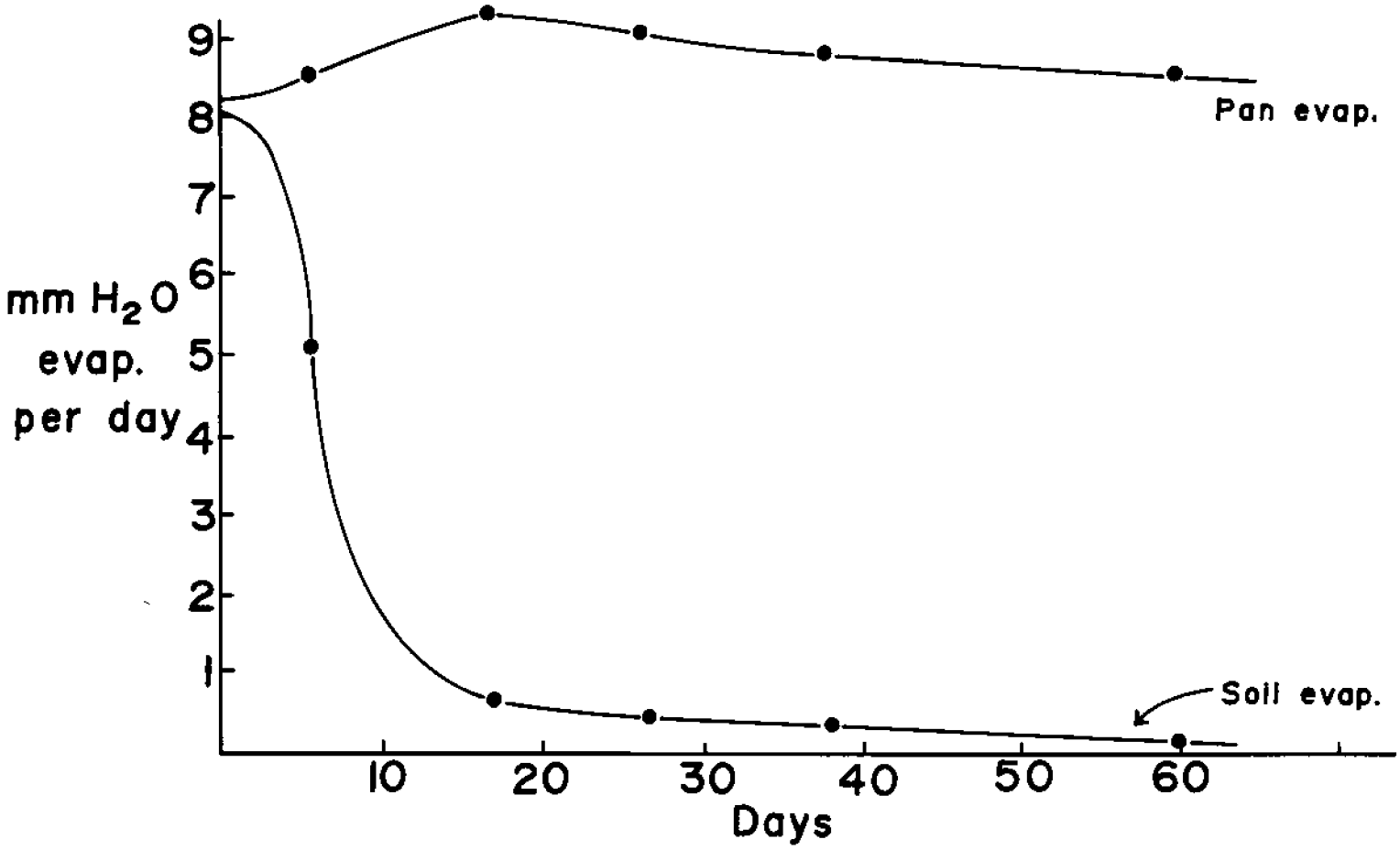


Figure 5-2. Comparison of evaporation from bare soil to a free water surface.

soil temperature measurements on the silt loam soil in southern Idaho (Cary and Wright, unpublished data). During a warm afternoon in June, the net radiation was 2 or 3 % less over a smoothly packed plot than over the granular hand-raked surface of the control. Daytime soil temperatures at the 6-cm depth were about 2.5° C warmer under the packed surface than under the control. This temperature increase disappeared during the night because of the greater upward heat flux described by Gradwell (1963). Infrared measurements of afternoon surface temperatures showed about the same trend as the 6-cm soil temperatures.The higher soil temperatures in the packed plot resulted from a greater downward conduction of energy from the soil surface. The lower net radiation of the packed plot suggests that it had a significantly lower sensible heat flux to the air than did the rougher check surface.

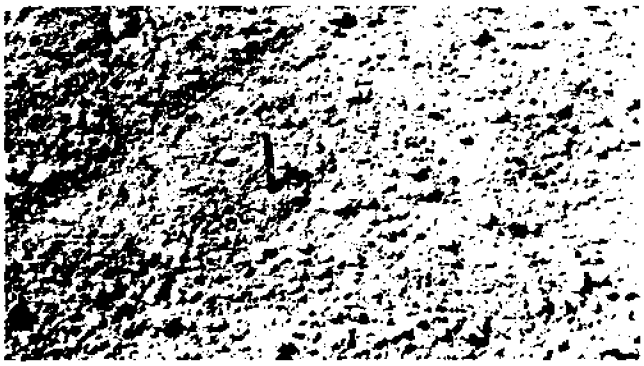
It appears from these observations, that one should not expect a soil crust to affect the heat flux across the soil-atmosphere interface by more than a few percent unless there is a large increase in bulk density, an obvious change in surface color, deep cracking to encourage greater evaporation of soil moisture, or a reduction in plant cover.

Transport of Liquid Water through Soil Crusts

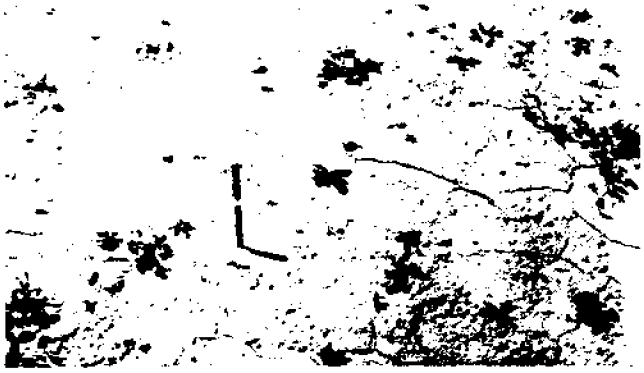
Theory

A description of the classical theory of water flow in soil has been reviewed by Miller and Klute (1967). The movement of water within a soil is described by a

Figure 5-3. Crusts formed for the heat exchange study: 1. Dry mulch. 2. Sprinkled with ponding. 3. Gentle rain without ponding. 4. Surface irrigated with ponding. 5. Ponded and puddled.

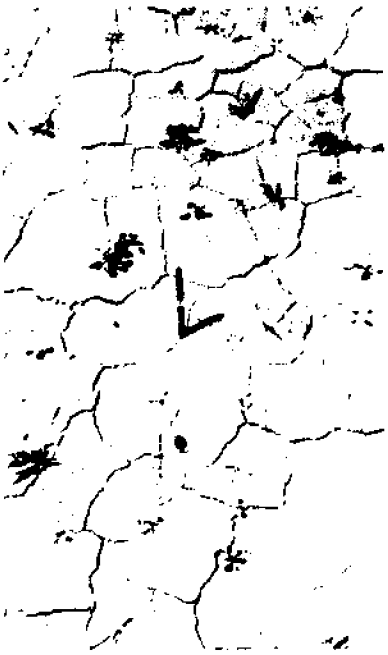


PLOT 1

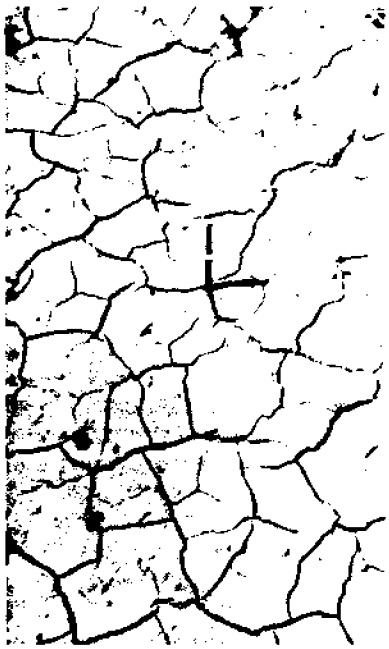


PLOT 3

PLOT 5



PLOT 2



PLOT 4

Darcy-type equation which, for the vertical direction only, is

$$J = K(dS/dz + 1) \qquad [5\text{–}4]$$

where J is the volume of flow per unit area per unit time, K is the hydraulic conductivity and a function of the water content, and dS/dz is the soil suction gradient in the z direction. Combining equation 5-4 with the conservation of mass principle for a small element of soil volume gives:

$$\frac{\partial\,(K\ \partial S/\partial z)}{\partial z} + \frac{\partial K}{\partial z} = \frac{\partial \theta}{\partial t} \qquad [5\text{–}5]$$

where θ is the moisture content.

Equation 5-5 has been solved by various techniques for simple cases to obtain the soil water content or soil suction as a function of depth and time, or the infiltration or evaporation rate as a function of time. The usual assumption is made that the soil is homogeneous and isotropic within the flow region under consideration. Philip (1957) solved equation 5-4 for a uniform soil and initial water content to obtain an equation which approximates the accumulated water intake I by the soil at various times after water has been continuously applied at the soil surface for $t > 0$. The solution was

$$I = At^{1/2} + Bt \qquad [5\text{–}6]$$

where A and B are soil parameters. Equation 5-5 has not been solved analytically for layered or crusted soils, though numerical solutions have been tested for flow into layered soils (Miller and Klute, 1967).

Hillel and Gardner (1969) considered the effect of a crust on the steady-state infiltration of water, that is, at a time when the wet front had reached a sufficient depth so that the infiltration rate was approaching a constant value. Under these conditions

$$J_c = J_u \qquad [5\text{-}7]$$

or

$$K_c[(dS/dz)_c + 1] = K_u[(dS/dz)_u + 1] \qquad [5\text{-}8]$$

where the subscripts c and u refer to the crust and subcrust, respectively. The suction gradient in the subcrust goes to zero under stead conditions, so that

$$J = K_u = K_c \frac{S_c - S_o + L_c}{L_c} \qquad [5\text{-}9]$$

where S_o and S_c are the soil suctions at the soil surface and the bottom of the crust, respectively, and L_c is the thickness of the crust. Assuming that $S_o = 0$, $L_c << S_c$ and S_c does not exceed the air entry value of the crust (i.e., K_c is constant and equal to the saturated conductivity), then

$$\frac{K_u}{S_c} = \frac{K_c}{L_c} \qquad [5\text{-}10]$$

or

$$J = S_c \frac{K_c}{L_c} \qquad [5\text{-}11]$$

Equation 5-11 then predicts that the steady-state infiltration rate will be less for thicker crusts and for those with lower conductivities.

In general, the theory indicates that the hydraulic properties of the crust and the subcrust interact to cause a steady infiltration rate and moisture profile. The suction in the subcrust adjusts to a constant value, creating a suction gradient across the crust sufficient to make the flow rate through the crust identical to the flow rate below the crust. Hillel and Gardner obtained laboratory results which agree reasonably well with theoretical predictions.

Of more general interest is infiltration of water under transient conditions, i.e., when the infiltration rate and soil moisture profile are changing with time. Hillel and Gardner, in a later paper (1970), examined the effects of a soil crust for transient conditions using an approach proposed by Green and Ampt (1911) and later by Philip (1957). The pertinent assumptions are: (1) there is a constant effective suction at the wetting front; and (2) there is a constant water content profile and hydraulic conductivity in the subcrust above the wetting front. These assumptions simplify the flow equation to a form amenable to analytical solution.

For a uniform profile and vertical infiltration, the Darcy-type equation giving the infiltration rate i at any particular time is

$$i = K \frac{S_f - S_o + L_f}{L_f} \qquad [5\text{-}12]$$

where S_f and L_f are the effective suction at the wetting front and the depth of the wetting front, respectively, S_o is the suction at the soil surface which may be taken as zero for a thin layer of water on the surface.

To account for the effect of a crust, we can write

$$J = K_u \frac{S_f - S_c + L_u}{L_u} \qquad [5\text{-}13]$$

where $S_f - S_c$ and L_u are the effective suction difference and the distance between the lower boundary of the crust and the wetting front, respectively. The equation applies only after the wet front has passed through the crust. If the crust is such that it initially saturates and remains saturated, then J is equal to the infiltration rate i and

$$S_c = \frac{i\,L_c}{K_c} \,. \qquad [5\text{-}14]$$

Also,

$$i = \frac{dI}{dt} = \triangle\,\theta\,\frac{dL_u}{dt} \qquad [5\text{-}15]$$

where I is the accumulated intake in the subcrust, and $\triangle\,\theta$ is the increase in water content between the crust

and the wetting front. Combining equations 5-15, 5-14, 5-13, and integrating over depth and time gives:

$$L_f - (S_f - L_c K_u/K_c) \ln \frac{S_f + L_f}{S_f} = \frac{K_u t}{\triangle \theta} \quad [5\text{–}16]$$

Equation 5-16 cannot be solved explicitly for L_f as a function of time. However, a trial and error procedure may be used to evaluate the depth of wetting as a function of soil properties and time. Again, as the thickness of the crust or the ratio K_u/K_c increases, the infiltration rate decreases.

Application of the theory

Edwards and Larson (1969), using a numerical analysis of infiltration through a surface seal into a homogeneous soil, found results in agreement with those predicted in the preceding section. From their study, they also predicted that the suction gradient in the surface layer should increase as K_c decreases and as K_u increases. This suction gradient increase could partially offset lower infiltration rates caused by low K_c values.

The theory predicts that the thicker and denser the crust, the lower the infiltration rate will be. The effect of change in porosity (or conductivity) on infiltration rate is illustrated in Figure 5-4 by data published by Miller (1969). The wetting front moving from the silt loam soil into the sand layer is analogous to wetting front moving through a compacted dense crust and into the more porous soil below.

An increase in exchangeable Na at the soil surface leads to dispersion and plugging of the larger pores during periods of high water content. Water flow conditions then become those described by the layered soil theory. However, as soluble salts are leached from the soil surface, K_c will not be constant, but will decrease rapidly and this must be accounted for in any analysis. As pointed out in Chapter 2, Figure 2-3, calcium may be added to the soil's surface to alleviate this problem.

Though cracks are not really covered in detail in any mathematical formulation of infiltration, they are extremely important in increasing the initial entry of water into dry crusted soils (Ritchie et al., 1972). In some heavy clay soils, cracks more than 10 cm wide and over 50 cm deep may develop. Cracks of this size increase the total surface area of the soil-atmosphere interface by 3 to 5 times (Adams et al., 1969), as well as being very effective in trapping runoff water. Even relatively small cracks such as those shown in Figure 5-3 increase infiltration during the initial period of surface wetting. Because of a lack of cracking, a high sand content in a soil surface crust may actually be detrimental to infiltration. Kemper and Noonan (1970) found that maximum runoff from rain falling on crust-prone soils occurred when the sand content was between 50 and 80%.

A soil crust may also affect the upward movement of liquid phase water in at least two ways. If the crust if severe enough to restrict the intake of water during wetting, the final moisture content of the soil immediately below it will be lower than if the intake had been normal. This will generally be true even if the infiltration time is extended so that the total net intake for the restricted and normal cases are the same. A lower moisture content below the crust will result in a lesser upward movement of liquid phase soil water in response to evaporation from the surface.

A second and more direct way in which a crust may control upward movement of soil water results from abrupt changes in pore size distribution. As water moves from a soil layer with one given pore size distribution into a layer with a different size distribution, the suction gradient will remain fairly smooth and continuous, but because of the different water-holding capacities of the different layers at a given suction, the moisture content gradient may change abruptly. In a transient unsaturated system, increasing the outflow rate requires an increased water tension gradient. This requires a decrease in moisture content. Generally, when comparing unsaturated soils, a lower water content indicates a lower liquid conductivity, and an increase in tension can cause a sharp drop in conductivity. The drop in conductivity forces even a larger change in tension gradient, which produces yet a lower conductivity, and soon the liquid flow becomes very small.

Another good example of the effect of the discontinuity in pore size is shown by the data of Bresler and Kemper (1970) in Figure 5-5. In this experiment, columns of crust-prone soil were wet by rain with NaCl on the surface, by flooding, and by slow infiltration through filter paper. These treatments resulted in a decreasing severity of crusts. The surfaces were allowed to begin drying, and the conductivity calculated 1, 2, and 4 hours later. The soil's resistance to water flow (1/K) is

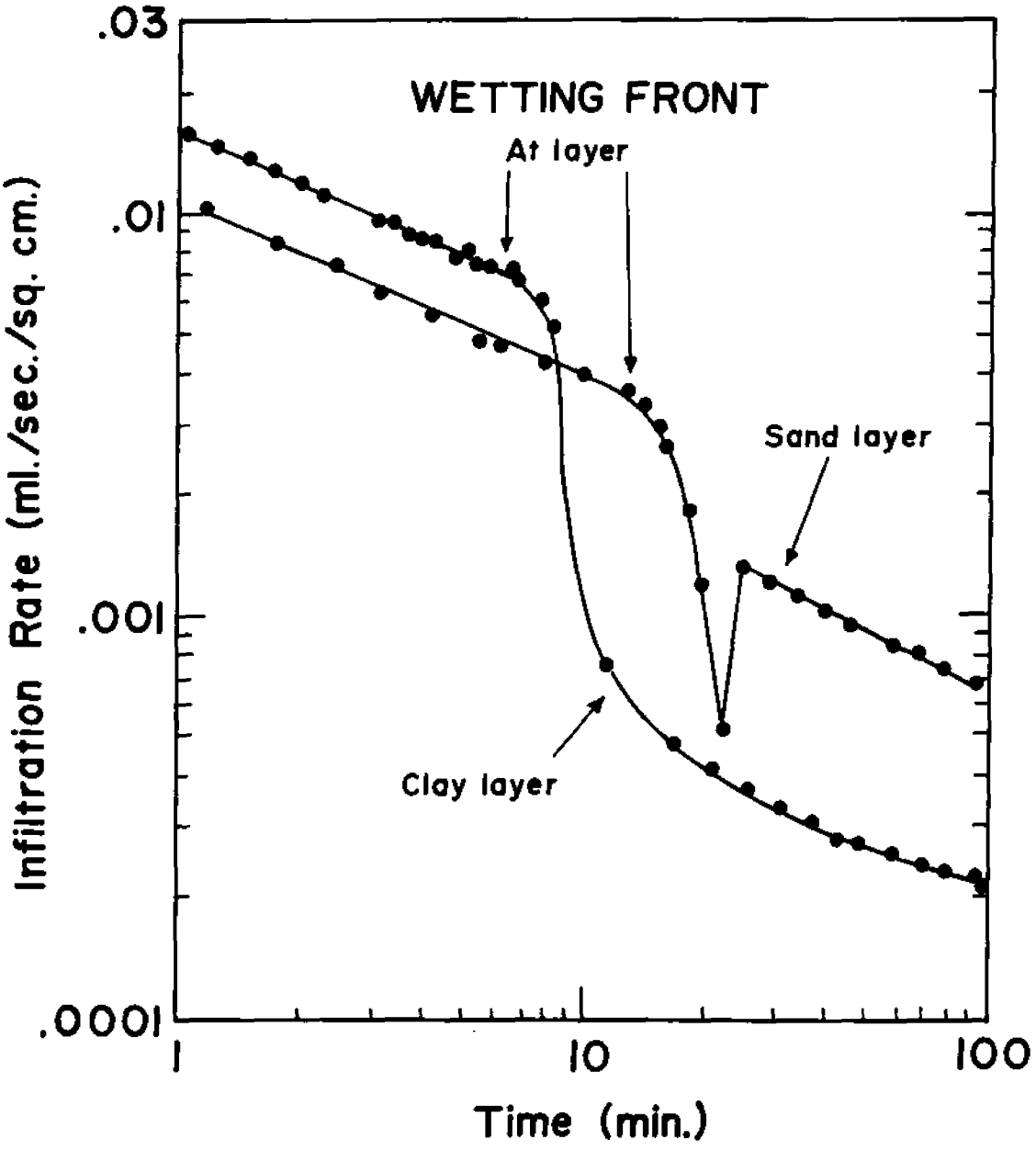
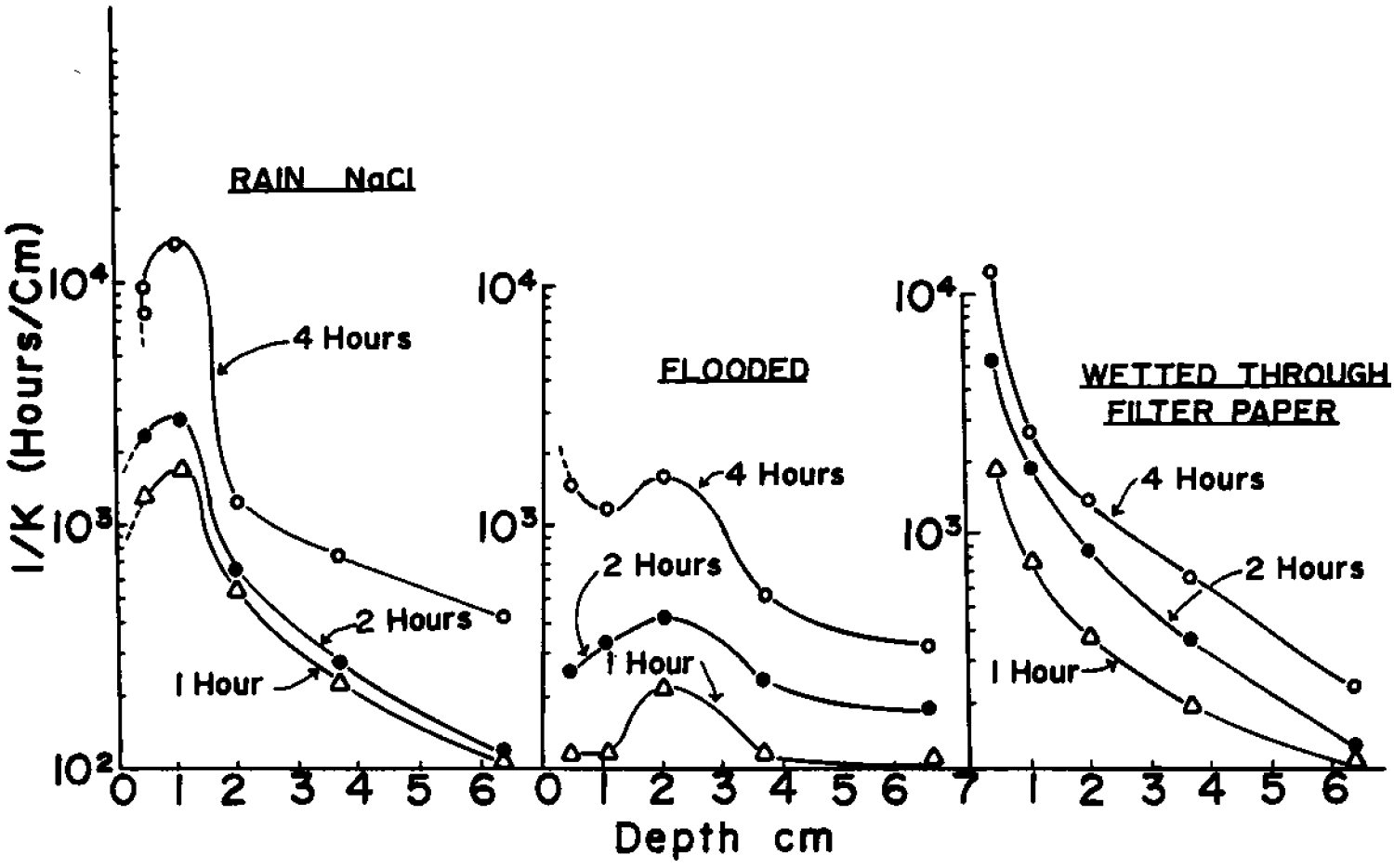


Figure 5-4. Effect of sand and clay layers on infiltration rate into Palouse silt loam as function of time (Miller, 1969).

plotted in Figure 5-5 and clearly shows the increase which developed between the crust and the underlying soil. The greater the discontinuity, the sooner liquid phase flow will approach zero at the crust-soil interface during high evaporative demands at the surface.

By way of general conclusions, one must realize that a soil crust can reduce water intake by one or two orders of magnitude, and the result may be flooding and erosion. Effects of crusts on water vapor and heat exchange between the soil and the atmosphere are more subtle, but nonetheless real. The extent and depth of cracking, soil density, surface texture, and color are important. Severe soil crusts may ultimately have the greatest effects on water and energy exchange by preventing the establishment of plants, including weeds.

Figure 5-5. The resistance of soil to water flow (1/K) as a function of soil depth for 3 soils with decreasing degrees of surface crusts. The curve parameters are hours after drying had begun (Bresler and Kemper, 1970).



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